

**Sensor to User –
NASA/EOS Data for
Coastal Zone Management Applications Developed from
Integrated Analyses**

Verification, Validation and Benchmark Report

**National Aeronautics and
Space Administration**

**John C. Stennis Space Center
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Executive Summary

The NASA Applied Sciences Program seeks to transfer NASA data, models, and knowledge into the hands of end-users by forming links with partner agencies and associated decision support tools (DSTs). Through the NASA REASoN (Research, Education and Applications Solutions Network) Cooperative Agreement, the Oceanography Division of the Naval Research Laboratory (NRLSSC) is developing new products through the integration of data from NASA Earth-Sun System assets with coastal ocean forecast models and other available data to enhance coastal management in the Gulf of Mexico. The recipient federal agency for this research effort is the National Oceanic and Atmospheric Administration (NOAA).

The contents of this report detail the effort to further the goals of the NASA Applied Sciences Program by demonstrating the use of NASA satellite products combined with data-assimilating ocean models to provide *near real-time information* to maritime users and coastal managers of the Gulf of Mexico. This effort provides new and improved capabilities for monitoring, assessing, and predicting the coastal environment. Coastal managers can exploit these capabilities through enhanced DSTs at federal, state and local agencies. The project addresses three major issues facing coastal managers: 1) Harmful Algal Blooms (HABs); 2) hypoxia; and 3) freshwater fluxes to the coastal ocean.

A suite of ocean products capable of describing “Ocean Weather” is assembled on a daily basis as the foundation for this semi-operational multiyear effort. This continuous real-time capability brings decision makers a new ability to monitor both normal and anomalous coastal ocean conditions with a steady flow of satellite and ocean model conditions. Furthermore, as the baseline data sets are used more extensively and the customer list increased, customer feedback is obtained and additional customized products are developed and provided to decision makers. Continual customer feedback and response with new improved products are required between the researcher and customer.

This document details the methods by which these coastal ocean products are produced including the data flow, distribution, and verification. Product applications and the degree to which these products are used successfully within NOAA and coordinated with the Mississippi Department of Marine Resources (MDMR) is benchmarked.

1.0 Introduction

1.1 NASA Applications and Mission Traceability

The NASA vision and mission statements include a clear focus on the Earth and on life Earth. The NASA Science Mission Directorate is the primary manifestation of NASA's mission in Earth science and applications. As part of a systematic approach to extending the benefits of NASA's mission in Earth science to the broader community, NASA identified 12 applications of national priority using such criteria as consideration of potential socio-economic return, application feasibility, appropriateness for NASA, and partnership opportunities. The Applied Sciences Program of the Science Mission Directorate, in partnership with public and private organizations, employs a systems engineering process to integrate and benchmark NASA inputs into operational Decision Support Systems (DSSs) across these 12 application areas, one of which is Coastal Management.

The Coastal Management Program Element extends Earth science research results, products derived from Earth science information, models, technology, and other capabilities into partner DSTs for coastal (including marine and ocean) management issues. The Coastal Management Program supports partners on issues of concern related to coastal zones, nearshore environments, marine and open-ocean activities, wetlands, estuaries, reefs, oceanic islands, and coasts of large inland waters. The Program focuses on decision tools serving the following classes of issues related to coastal, marine, and oceanic regions:

- Environmental resource management;
- Economic management and trade;
- Emergency management and response;
- Mitigation and adaptation of sea level changes; and
- Public and environmental health.

The Coastal Management Program's goal consists of the following tenets:

- Develop and nurture partnerships with appropriate coastal organizations;
- Identify and assess partners' coastal management responsibilities, plans, and DSTs and evaluate capacity of Earth science results to support the partners;
- Validate and verify application of Earth science results with partners, including development of products and prototypes to meet partners' requirements. With partners, document value of Earth science results relative to partners' benchmarks and support;
- Support adoption into operational use; and

- Communicate results and partners' achievements to appropriate coastal communities (FY2006 – 2010 Coastal Management Program Element Plan).

Near-term validation and benchmarking efforts include data products derived from the Terra, Aqua, and Landsat satellites. Future missions such as Global Precipitation Measurement (GPM), Ocean Surface Topography Mission (OSTM), and Aquarius will provide precipitation, sea surface height, and salinity data of relevance to this application.

This report satisfies FY06 IBPD metric 5ESA4.G, 8.7: benchmarking at least 5 DSSs through Earth system science models and benchmarking the use of Earth science observations and predictions from Terra and Aqua data.

1.2 Introduction to Integrated Ocean Analyses

Integrated ocean analysis in the Gulf of Mexico is a decision support effort that intensively utilizes NASA and NOAA satellite imagery combined with ocean circulation models to systematically output products into an automated real-time database to characterize the “ocean weather” in the Gulf of Mexico. Present capability in monitoring coastal ocean conditions is limited by the inability to assemble all critical components to define ocean processes that are required for real-time decision making. Different and diverse data sources for physical ocean conditions and unreliable satellite data products limit the coastal manager’s ability to monitor the environment on a continual real-time basis. This effort provides a much needed capability to assemble ocean data products and make them readily available for NOAA partners and direct access to the coastal managers.

The assemblage of the data combined with new software interfaces (such as the Applied Coherent Technology Inc. (ACT’s) WWW Information Processing Environment (WIPE) and the NOAA NCDDC – HABSOS) allows methods for easy access to multiple data sets and provides a unique capability for monitoring and detecting changes in the ocean environment on scales of hours, days, weeks and years. These data management utilities combined with a wealth of ocean products require data manipulation and design of customized user-specific products for coastal management. The overall goal is to maximize the value of satellites from NASA’s Earth Observing System (EOS) to the coastal management decision maker and educator. The project has been an assemblage of partners from the following organizations:

1. **NASA –Applied Sciences – Stennis Space Center, MS**
2. **Naval Research Laboratory (NRLSSC) – Oceanography Division- Stennis Space Center, MS**
3. **Applied Coherent Technology, Inc. (ACT) – Reston, VA**

4. NOAA Centers --

- **National Coastal Data Development Center (NCDDC)**, as part of the National Environmental Satellite Date Information Service (NESDIS), supports ecosystem stewardship by providing access to the nation's coastal data resources.
- **Coastal Services Center (CSC)**, as part of the National Ocean Service (NOS), fosters and sustains the environmental and economic well-being of the coast by linking people, information, and technology.
- **CoastWatch Program** (NESDIS) processes near real- time oceanographic satellite data and makes it available to Federal, state, and local marine scientists, coastal resource managers, and the general public.
- **Center for Coastal Monitoring and Assessment (CCMA)**, as part of NOS, assesses and forecasts coastal marine ecosystem conditions through research and monitoring.

This program provides a cooperative environment to --

- Provide an end-to-end pipeline - from EOS input, through data extraction services, emerging scientific algorithms, Web technologies, and applications – providing meaningful, easy to use environmental products to a diverse community of Coastal Zone Management decision makers, educators, students and the interested residents of our nation's coastal areas.
- Provide new interoperability between data supplier and end-user with emphasis on time critical and continuous ocean data products for the Gulf of Mexico. Use GIS and Internet enabled applications to deliver high quality EOS based products.
- Conduct focused research for specific improved ocean properties that are customized and respond directly to guidance of targeted customers in collaboration with NOAA.

The following objectives guide this collaborative effort:

- Generate new products and improve existing products from Earth science satellites and models to support coastal ocean resource managers;
- Integrate model and satellite output to address Coastal Management issues identified from NOAA and other partners;

- Enable real-time ocean properties to be easily assembled and distributed into coastal products through web technology and OPeNDAP (Open-source Project for a Network Data Access Protocol) distribution servers;
- Automate product creation to permit applications experts to address product content/quality (more time on analysis of data products);
- Through partners, expand an Internet-enabled system architecture to reach all levels of applications providers and end-users;
- Concentrate data/product distribution efforts on appropriate, commonly-used formats;
- Cooperate with NOAA NOS and NESDIS to ensure useful product creation and integration with current NOAA decision support tools and priority needs of the coastal resource management community;
- Establish partnerships with NOAA, NASA, and NRLSSC in serving the coastal resource management community;
- Identify targeted customers for ocean products with NOAA and NASA;
- Determine the effectiveness of these ocean properties to the decision making process.

To address the goals and objectives within this collaboration, an interagency and commercial agreement was established to define a working relationship providing new capability to the coastal management community and decision support. Figure 1 outlines the breakdown of the partnership components.

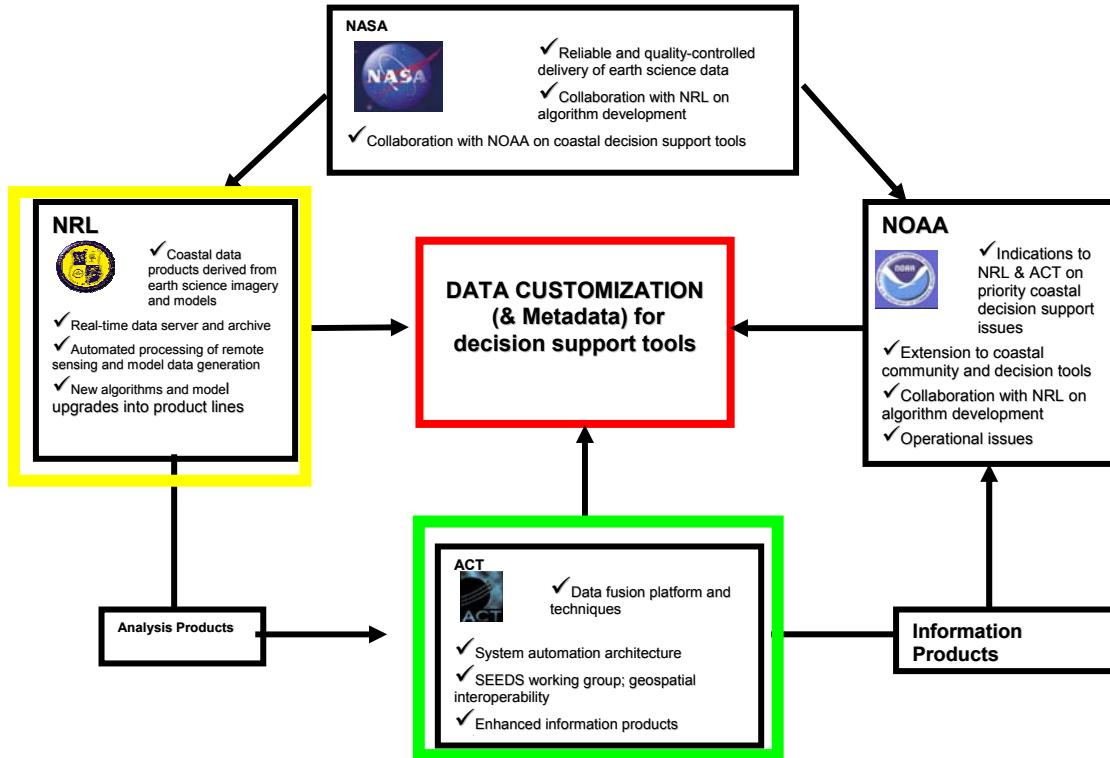


Figure 1: Outline of agency roles in NASA REASoN effort. Yellow box reflects the research component responsibilities; green box reflects the ACT application component responsibilities

The project tasks are separated into two key components, a product research and development component accomplished by NRLSSC and an application development component accomplished by ACT.

The product research/development component provides state-of-the-art oceanographic expertise and research to address issues related to generation of new geophysical data products as part of a production pipeline. The following tasks comprise this effort:

- Establish a new real-time ocean properties data stream for the Gulf of Mexico from NASA and NOAA satellites and numerical circulation models;
- Demonstrate rapid access for monitoring ocean conditions;
- Demonstrate real-time monitoring of ocean conditions;
- Develop remote sensing bio-optical and thermal ocean properties (from MODIS (Terra and Aqua) and the NOAA Advanced Very High Resolution Radiometer (AVHRR));
- Model three-dimensional physical ocean properties with the Navy Coastal Ocean Model (NCOM);

- Integrate remote sensing products and modeling products available through the OPeNDAP server into NOAA's NCDDC GIS data structure;
- Identify new applications of ocean properties for monitoring coastal waters;
- Create new customized ocean products for target focus areas (HABS, Freshwater discharge);
- Rapidly adapt and demonstrate new algorithms that generate relevant ocean properties to support coastal management.

The application development component works directly with NOAA partners to provide a pipeline architecture that addresses issues related to data integration or ingest, processing, distribution, access, and decision support. The following tasks comprise this effort:

- Automate product creation to permit experts to spend more time on product content and quality;
- Expand an Internet-enabled system architecture to reach to all levels of applications provider and end-user, particularly NOAA CoastWatch data system and HABSOS and its regional users;
- Concentrate data/product distribution efforts on commonly-used formats, particularly in Geographic Information Systems (GIS);
- Provide community awareness of ocean products and inter-connectivity to users and managers (State, Federal and commercial customers);
- Provide the link of the researchers and customers through workshops and seminars.

To examine the accuracy, efficiency and effectiveness of this multi-faceted research-to-applications initiative, individual components are discussed in the next section. These components include coastal remote sensing, ocean modeling, data integration, data delivery, verification and application to coastal management. We will present an application of these integrated products for decision support use by the Mississippi Department of Marine Resources (MDMR). For benchmarking, many of these integrated products were not previously available to support coastal management at MDMR. Discovery of new applications, e.g., ecosystem identification, continues through project interaction with NOAA and MDMR users.

1.3 Purpose of This Report

The purpose of this report is to capture, through the application of systems engineering principles, the current status and future course of the REASoN project ***“Integrated analyses of ocean data and distribution for support of coastal managers in the Gulf of Mexico”***. This report identifies the current capability for real-time ocean weather from satellites and ocean models, and the methods and algorithms used in providing these data. The basis and validation of these algorithms and the quality of products are determined. Additionally, this report identifies how these products are transferred between Federal, state and commercial users and, ultimately, how they are transitioned to customers. This report details examples of coastal products currently in use and how new products are identified as potential products for use by coastal zone managers. Lastly, metrics of the program capability for real-time product development, distribution, and dissemination are assessed for their impact on coastal management. This report assesses the data gaps of and the necessary improvements to present and future remote sensing and modeling developments for coastal applications.

2.0 Summary of Systems Engineering Activities

Many elements, from the study location to the eventual coastal decision product, are inherent to overall project evaluation and successful application. These parts are examined within the context of a systems engineering approach for assessment of the system as a whole.

2.1 Study Area

The Gulf of Mexico is a relatively complex ocean region in which both major ocean circulation and coastal circulation occur. The interaction of the Loop Current with coastal circulation creates significant exchange of open-ocean and coastal water properties. Mississippi River outflow further divides the Gulf ocean region into a variety of optical and physical provinces. For coastal management decision-making, the environmental complexity of the Gulf of Mexico requires real-time updates on coastal ocean conditions. Within the Gulf of Mexico, monitoring and assessment for NOAA and other operational and regulatory agencies focuses on key issues such as harmful algal blooms (HABs), hypoxia, and fresh water outflow

The Gulf of Mexico supports a plethora of economic and social interests for the entire United States. Coastal regions of the Gulf of Mexico define diverse environments that affect marine operations dealing with vacation resorts and recreational impacts; marine shipping and navigation; commercial fishing and shellfish harvest; wetlands management; oil and gas exploration, including pipeline management and restoration; pollution monitoring related to agriculture and harbor impacts on coastal waters; and harbor security. (Two of the ten largest ports in the world are Houston, Texas, and New

Orleans, Louisiana, and 52.3% of the tonnage reaching the US by waterways transits through the Gulf of Mexico (NOAA 1999).

This demonstration project for the Gulf of Mexico provides a future look at coastal monitoring and near real-time use of research capabilities available on a twenty-four hours/seven-days-a-week (24/7) basis for managing the coastal environment.

2.2 Coastal Remote Sensing

Ocean color satellites and the ability to detect biological, geological, and optical processes within ocean waters have advanced significantly in the last five years. Research has demonstrated the capability to uncouple the water signature into its fundamental components using spectrophotometric methods (Arnone and Gould, 1998; Arnone *et al.*, 2003). The ability to resolve these properties has extended the utility of these satellite platforms beyond research applications. Satellites can now be used in management applications such as monitoring coastal waters for river plume discharge and the distribution of colored dissolved organic material (CDOM) along the coast. These properties are used as tracers for pollution discharge and for applications such as swimmer/diver visibility and monitoring of coastal waters (Arnone, 1999). Spectral, optical remote sensing signatures are used for determining the backscattering coefficient of marine and terrigenous particles (particulate organic matter (POM) and particulate inorganic matter (PIM)). PIM and POM are used to understand biological distributions and bottom resuspension processes of suspended particles in shallow coastal regions. Satellites provide a means to trace river sediment plumes associated with resuspension events. Real-time animation of sequential satellite image products can be used to determine the mixing and dispersion of these events in shelf waters (Arnone *et al.*, 2002).

Backscattering of marine particles is also used to track open-ocean and coastal evolution of phytoplankton blooms and their subsequent decay, processes that can have a significant impact on shellfish and fisheries industries. In addition, ocean water absorption signatures can be separated into contributions from CDOM, non-photosynthetic particles, and pigmented material such as chlorophyll. Satellite-derived CDOM absorption provides a method for identifying terrestrially derived material such as humic and fulvic acids carried from rivers into the coastal ocean. The conservative nature of CDOM in the coastal ocean has permitted its use as a tracer of the salinity field and estuarine and river discharge.

NRLSSC has developed algorithms for ocean color sensors for the last 8 years and has developed extensive algorithms to deconvolve ocean color spectral signatures into optical components. Algorithms have been developed for the Sea-viewing Wide Field-of-View Sensor (SeaWiFS, OrbImage) and the NASA Moderate Resolution Imaging Spectrometer (MODIS). The robustness of these algorithms insures their applicability to future satellites.

Currently, NRLSSC processes individual satellite images into quantitative products for ocean and coastal monitoring (Table 1).

Table 1. Products and associated applications derived from NASA and other satellite sensors.

Product	Application
Chlorophyll concentrations	biological processes – blooms and decays of algal blooms both harmful and non-harmful
Spectral backscattering	particle concentration, organic (marine) and inorganic (terrigenous) particles, resuspension
Spectral absorption	total absorption, changes in water quality
Spectral colored dissolved organic matter (CDOM)	conservative tracer of river plumes, linked with coastal salinity, photo-oxidation processes
Spectral particle absorption	particle composition (organic / inorganic particles)
Spectral phytoplankton absorption	linked to pigment packaging effects within phytoplankton cells
Remote sensing reflectance	absolute water color
Attenuation coefficient (k532)	light penetration depth, light availability at depth
Aerosol concentration	type and distribution – atmospheric visibility
Beam attenuation coefficient	total light attenuation
Swimmer visibility	horizontal viewing near the surface
Sea surface temperature (SST)	skin temperature

The spatial and temporal variability observed in these products provides the framework for understanding basic processes underlying water mass movement and environmental change. Algorithms used for product development within this project are refined by

leveraging activities sponsored through other research programs at NRLSSC and NASA (e.g., SIMBIOS).

2.2.1 Satellite Processing

NRLSSC developed the Automated Processing System (APS) for implementation of advanced algorithms for ocean color and sea surface temperature (SST) retrievals from NASA and NOAA satellites. APS processes real-time satellite data from SeaWiFS and MODIS Terra and Aqua for selected regions using high performance LINUX computing systems. This automated processing software includes calibration, atmospheric correction, ocean algorithms, image geo-registration, and browse image transfer to the web (<http://www7333.nrlssc.navy.mil>). All APS data products are organized in standard hierarchical data file (HDF) format. APS was initially developed for Navy research applications and, as such, provides a method to rapidly and easily reprocess satellite data sets to test and refine new algorithms. APS is closely coordinated with NASA satellite data processing programs and software. NRLSSC maintains close ties with NASA and university calibration teams in order to implement software developments required for accurate products. The capability extends beyond the standard NASA products to test and implement applications in the coastal zone for coastal managers. Processing includes level 1 SeaWiFS and MODIS data from the NRTPE (NOAA Real-Time Processing Environment) to the regional data base located in OPeNDAP.

2.2.2 MODIS Terra and Aqua

MODIS Terra and Aqua overpasses are at ~0930 and ~1400 local time for the ocean color and sea surface temperature (SST) products, respectively. Additionally, Terra and Aqua night SST overpasses are at 2000 and 0200 local time. The ocean channels are at 1-km resolution with additional 500-m and 250-m channels that can be used for coastal waters.

NRLSSC works closely with NASA and the MODIS Science Team on the processing of MODIS data. NRLSSC processes the 1-km MODIS Aqua data using the MSL12 software developed through NASA Goddard Space Flight Center (GSFC) and modified to include coastal atmospheric correction and coastal algorithms. The 1-km MODIS Terra data are processed using the University of Miami code (Evans -- reference) and integrated with NRLSSC APS atmospheric correction and in-water coastal algorithms. (The MSL 12 software from Goddard currently does not process the Terra satellite.) NRLSSC is one of three national facilities capable of processing MODIS imagery into ocean products. NRLSSC processes the 250-m MODIS data from Aqua and Terra by combining the aerosol model for the 1-km channels with channels 1 and 2 (Arnone *et al.*, 2002).

Collectively, this project has processed daily real-time Gulf of Mexico imagery from MODIS (Terra and Aqua) for the past two years (approximately 10 GB of image data per day). The project provides daily quality control, refinement, and calibration of existing algorithms and satellite maintenance algorithms to the processing environment. New

algorithms and refinements to algorithms are updated periodically to insure operational products are as current as possible. Table 1 outlines the satellite sensor, its relevant characteristics, and some of the data products created from NRL processing allocated to this project effort. Figure 2 is an example of an NRL-processed image for beam attenuation within the Gulf of Mexico.

Table 2. Spatial resolution, temporal coverage, pertinent products, and approximate daily overpass times for satellite sensor data relevant to NRL processing for this project.

Satellite	Spatial resolution	Repeat Coverage	Some Products	Time of Overpass (local)
SeaWiFS	1km	1/day	Absorption (Chlorophyll a), CDOM, Backscattering, K532, Salinity	~11:30
NOAA-13, 14, 16	1km	6/day 3day/3night	Sea Surface Temperature	02:00 and 14:00
MODIS – Terra	1km (250m, 500m)	1/day (color) 2/day (SST)	Absorption (Chlorophyll a), CDOM, Backscattering, K532, Salinity, SST	09:30- 10:00
MODIS – Aqua	1km (250m, 500m)	1/day (color) 2/day (SST)	Absorption (Chlorophyll a), CDOM, Backscattering, K532, Salinity, SST	14:00 and 02:30

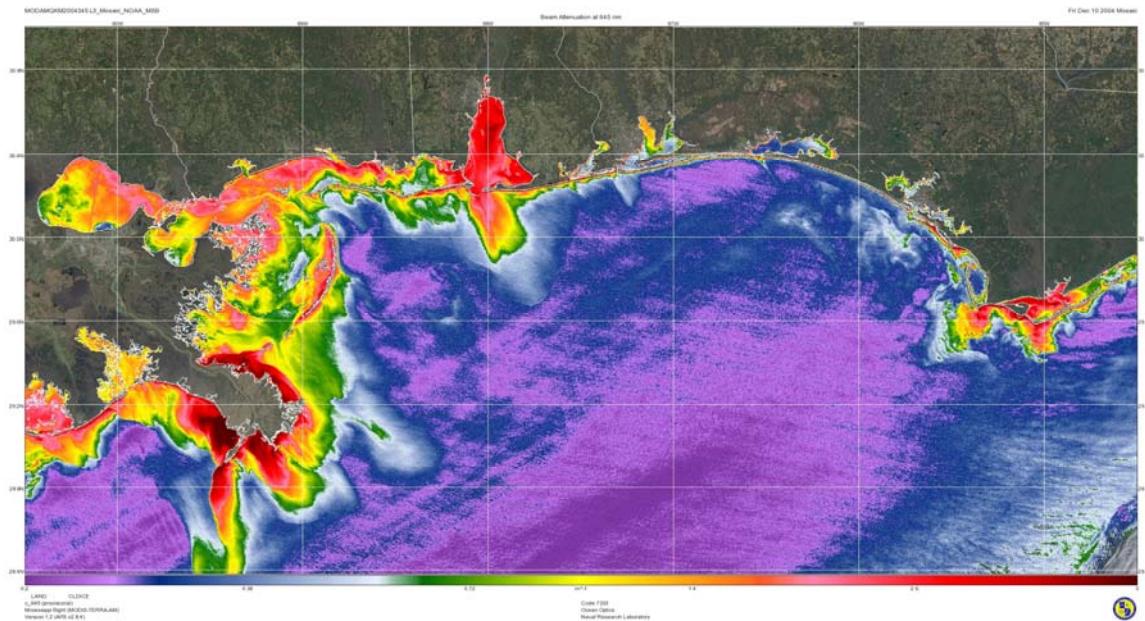


Figure 2: MODIS 250-m product of the beam attenuation coefficient for the Mississippi Bight within the Gulf of Mexico (Arnone et al, 2002.)

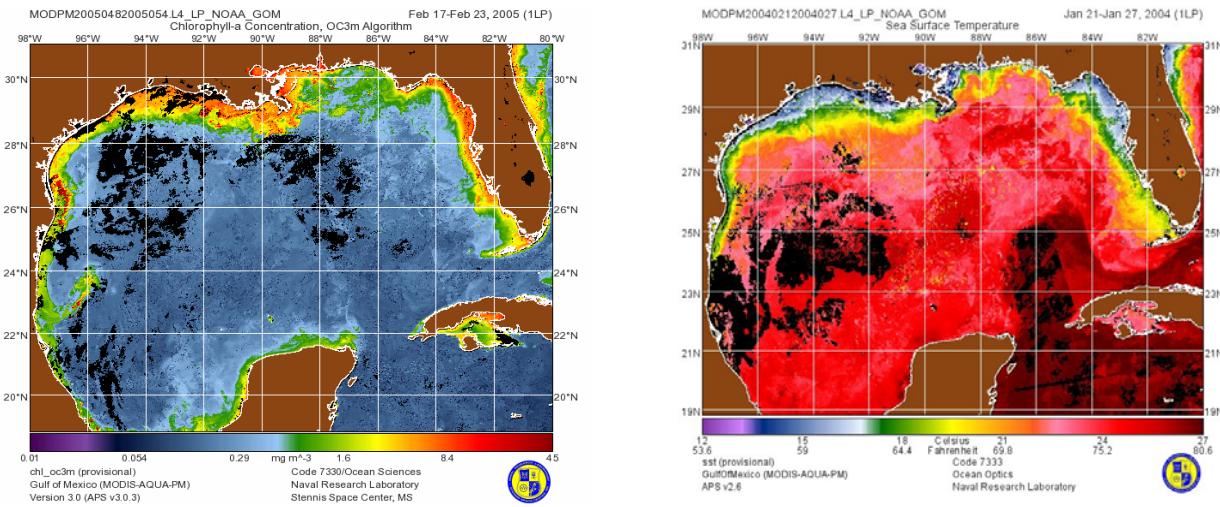


Figure 3: Examples of MODIS 1-km latest pixel composite chlorophyll concentration and SST (Sandige et al, 2002). The most recent product for a 7-day time period is used to provide daily ocean products. These examples illustrate the tracking of ocean features by reduction in cloud coverage.

2.2.3 Satellite Products

Presently, there are 426 satellite products produced per day from MODIS (Terra and Aqua) and AVHRR to support integrated analyses. Ocean environmental data are automatically generated daily for characterizing the ocean environment of the Gulf of Mexico. All satellite data for the Gulf of Mexico are obtained from either the NRLSSC SeaWiFS/MODIS receiver for the Gulf of Mexico or the NASA/NOAA real-time processing environment (RTPE) at Goddard Space Flight Center.

These data are processed within 3-4 hours of delivery using APS and are stored in a database and on an OPeNDAP server. NRL has developed algorithms to alleviate persistant cloud contamination within coastal images. On the OPeNDAP server, the following options are available for analysis by the user: individual satellite images; daily composite images (composite of all satellite images collected on that day); latest pixel composites (most recent valid pixel within a week, Figure 3); weekly composites; monthly composites; and annual composites.

2.2.4 Algorithms Used for Ocean Products

2.2.4.1 Chlorophyll Concentration

NASA developed empirical algorithms for computing surface chlorophyll concentration from SeaWiFS (OC4 algorithm) and MODIS (OC3 algorithm) ocean color satellites (O'Reiley et al., 1998; Campbell et al., 2006). These empirical algorithms were developed via nonlinear regression (4th degree polynomial) between *in situ* surface chlorophyll values and the ratios of remote-sensing reflectance (Rrs) at different channels. To derive chlorophyll values, the SeaWiFS OC4 algorithm uses the maximum among the ratios of $Rrs(443)/Rrs(555)$, $Rrs(490)/Rrs(555)$ and $Rrs(510)/Rrs(555)$, while the MODIS OC3 algorithm uses the maximum between the ratios of $Rrs(443)/Rrs(551)$ and $Rrs(488)/Rrs(550)$. These empirical algorithms do not and cannot separate the spectral signature into optical components and, thereby, do not specifically account for the contributions of CDOM, detritus and particle backscatter except in the intrinsic manner of how the empirical algorithms were developed. As the effects of these additional optical components become larger and regionally dependent in coastal waters, the retrieved chlorophyll values have a higher degree of uncertainty if regional variation is not accounted.

2.2.4.2 Coastal Optical Properties from the Quasi-Analytical Algorithm

The Quasi-Analytical Algorithm (QAA), developed by Lee et al. (2002), derives inherent optical properties (IOPs) of optically deep and coastal waters. Inherent optical properties can be obtained from the surface spectral signature of remote sensing reflectance. The IOPs provide new capability for understanding coastal processes and for monitoring coastal waters. New IOP products include the absorption and backscattering coefficients, which can be further uncoupled into phytoplankton absorption, detrital absorption and CDOM absorption. These components provide products for defining coastal processes (Arnone and Parsons, 2004).

QAA separates the inversion process into two consecutive partitions. The first partition is the derivation of coefficients of total absorption and backscattering. In this section, there is no involvement of spectral models for the absorption coefficient of phytoplankton pigments and CDOM, which then reduces uncertainties associated with those models. The second partition, which utilizes the derived total absorption coefficient from the first section, decomposes the total absorption coefficient into its major components. In the derivation of total absorption and backscattering coefficients, QAA follows the generally accepted model of remote-sensing reflectance and effectively utilizes the fact that water

absorption coefficients dominate most of the longer wavelengths. In the decomposition of total absorption (the second section), minimal spectral dependencies are employed regarding the contribution of phytoplankton and CDOM, in order to best retrieve the spectral signature of phytoplankton absorption.

NRLSSC has determined that the QAA algorithms provide the optimum results in coastal waters and are presently the algorithms used to retrieve products for the Gulf of Mexico.

2.2.4.3 Particulate Organic Matter and Particulate Inorganic Matter (POM/PIM)

The concentration and space/time distribution of the inorganic component (both river-borne and resuspended sediments) can be used to trace river plumes and fronts and can indicate regions of increased turbulence due to wave action and storm events. The distribution of the organic component does not necessarily mirror the distribution of the inorganic component, as they are influenced by different processes (physical vs. biological controls). Algorithms to remotely estimate both the concentrations and the optical characteristics (absorption and scattering coefficients) of the organic and inorganic constituents of the water would be very useful.

NRLSSC has developed algorithms to estimate the concentrations of total suspended particulate matter (SPM), particulate organic matter (POM), and particulate inorganic matter (PIM) from satellite ocean color imagery. These new satellite products provide a new capability to characterize processes in coastal areas. The products enable coastal managers to define the coastal distribution of resuspended sediments and particles that may derive from phytoplankton blooms. This capability enables new research products to determine how physical events (river plumes, wind resuspension, etc.) are different from the formation and decay of biological blooms.

The POM/PIM algorithms (Gould et al, 2002, 2006) were developed using *in situ* data collected within Gulf of Mexico coastal waters. Measured values of POM were regressed against phytoplankton absorption at 443 nm, $a_\phi(443)$, derived from filter pad analyses (reference). The rationale for this comes from an expected relationship between organic matter concentration and absorption due to chlorophyll at 443 nm, under the assumption that the distributions of organic matter and chlorophyll-containing particles co-vary. Similarly, SPM is estimated from a regression with the scattering coefficient at 555nm, $b(555)$. PIM is estimated from the difference between SPM and POM. Thus, using satellite-derived estimates of $a_\phi(443)$ and $b(555)$, remote-sensing estimates of PIM, POM, and SPM can be derived. The algorithms are validated with independent sets of *in situ* measurements.

To assess whether these new satellite-derived biogeophysical properties could be related to coastal oceanographic processes, relationships between the PIM/POM ratio and wind speed and wave height were examined. The premise is that bottom sediments (with higher PIM content than the water column) would be resuspended by waves during

periods of stronger winds, resulting in higher values of the PIM/POM ratio. In the turbid, shallow, coastal waters of the Mississippi Sound, a positive correlation between buoy-measured winds and waves and satellite-derived PIM/POM values was observed; i.e., stronger winds and higher waves lead to higher PIM/POM values. This provides indirect validation of the algorithms and indicates that these satellite-derived properties do relate to actual oceanographic processes; areas of elevated PIM/POM in the satellite imagery can potentially be used to map areas of higher resuspended sediments following wind events. The PIM and POM algorithms applied to MODIS images are used to develop daily products for the Gulf of Mexico.

2.2.4.4 Sea Surface Temperature

Sea surface temperatures are derived from the NOAA Advanced High Resolution Radiometer (AVHRR) and MODIS on the Aqua and Terra satellites. These products are available for both day and night satellite overpasses. Multi-channel SST (MCSST) algorithms using split window non-linear techniques are used.

AVHRR SST is computed using the calibration coefficients available with Level-1B data (Kidwell, 1991). The brightness temperatures for channels 3, 4, and 5 are used to estimate the sea surface temperature using a non-linear (NLSST) algorithm. The coefficients used in the NLSST are obtained from the NAVOCEANO SST processing system. The initial estimate used in the NLSST is derived from a multi-channel algorithm with coefficients obtained from NAVOCEANO. The cloud detection is based on Saunders and Kriebel (1998).

Generation of the sea surface temperature (SST) products from MODIS is currently performed using software developed by the Rosenstiel School of Marine and Atmospheric Science (RSMAS) at the University of Miami. The long-wave SST algorithm makes use of MODIS bands 31 and 32 at 11 and 12 μm , respectively. The brightness temperatures are derived from the observed radiances by inversion (in linear space) of the radiance versus blackbody temperature relationship. The nonlinear SST algorithm was tuned for two different regimes based on brightness temperature difference. Algorithm coefficients are continuously verified by RSMAS based on match-ups between the satellite retrievals of brightness temperature and field measurements of sea surface temperature. As currently implemented, these coefficients can be time-dependent. The coefficients are provided to msl12 through external files. For the MODIS instrument on Terra, the retrieved long-wave SST is further augmented by a time-dependent, mirror-side specific bias. The adjustment varies from -0.2 deg C to 0.1 deg C over the mission lifespan, and it is applied to mirror-side 1 only. The mirror-side correction was developed by RSMAS.

2.2.4.5 MODIS 250-m Coastal Products

The MODIS sensor on the Aqua and Terra satellites has 2 channels with a resolution of 250 meters. Channel 1 is centered at 648nm and channel 2 at 858nm. The increased resolution of these channels greatly enhances coastal applications of the 250-m products, but the limited spectral resolution restricts the typical atmospheric correction procedures used with 1-km ocean products. NRLSSC has developed a new atmospheric correction procedure which combines the 1km ocean channels and the 250m channels to produce a high resolution optical product of the beam attenuation coefficient called a *turbidity product* (Arnone et al, 2002).

The NRLSSC atmospheric correction procedure for the 250m (and 500m) channels of MODIS is an extension of the MODIS Ocean Science Team's multiple-scattering atmospheric correction. The atmospheric correction procedure includes calculations and correction for Rayleigh and aerosol scattering, surface glint, whitecap, and ozone contributions, as well as other gaseous absorption. The aerosol scattering correction procedure selects two aerosol models on a pixel-by-pixel basis using the 1km channels. The aerosol models describe the relationship between single-scattering aerosol reflectance and multiple-scattering aerosol reflectance. The 250-m channel 2 is used to estimate the single-scattering aerosol reflectance in the other channels. The two aerosol models from the 1km processing are used to convert the single-scattering estimate to multiple-scattering aerosol reflectance. Once the aerosols are removed from channel 1, along with the Rayleigh scattering and other corrections, the remaining ocean reflectance is used to determine the ocean properties.

The ocean reflectance in channel 1 is centered at 648nm in the red portion of the spectrum. At this wavelength, the beam attenuation coefficient is dominated by scattering and water absorption. The MODIS channel 1 beam attenuation (turbidity) algorithm was originally developed for the NOAA AVHRR sensor (Gould and Arnone, 1996). The attenuation coefficient algorithms have been tuned for channel 1 of MODIS and have been demonstrated to be stable and consistent in highly scattering coastal waters where particulate scattering dominates the signal.

2.2.5 Satellite Data Processing Levels and Systematic Development

Processing of satellite data evolved through a development cycle through a series of levels of processing. The flow is labeled as follows:

Level 1 – data from the RTPE which includes raw count satellite data with calibration coefficients and geometric registration tables imbedded into the data on a line-by-line basis. These are individual granules of daily scenes.

Level 2 - processing of the level 1 to include calibration to absolute radiance, atmospheric correction and in water geophysical units (for example, SST and Chlorophyll)

Level 3 – level 2 products geometrically registered and sub-sectioned into a map projection (Mercator)

Level 4 - level 3 products combined into daily mosaics or daily composites, mean and averaged merged, blended and latest pixel composite with statistics.

Level 5 – level 4 data assimilated into numerical models.

Examples of the level 3 and level 4 products are illustrated in Figure 4.

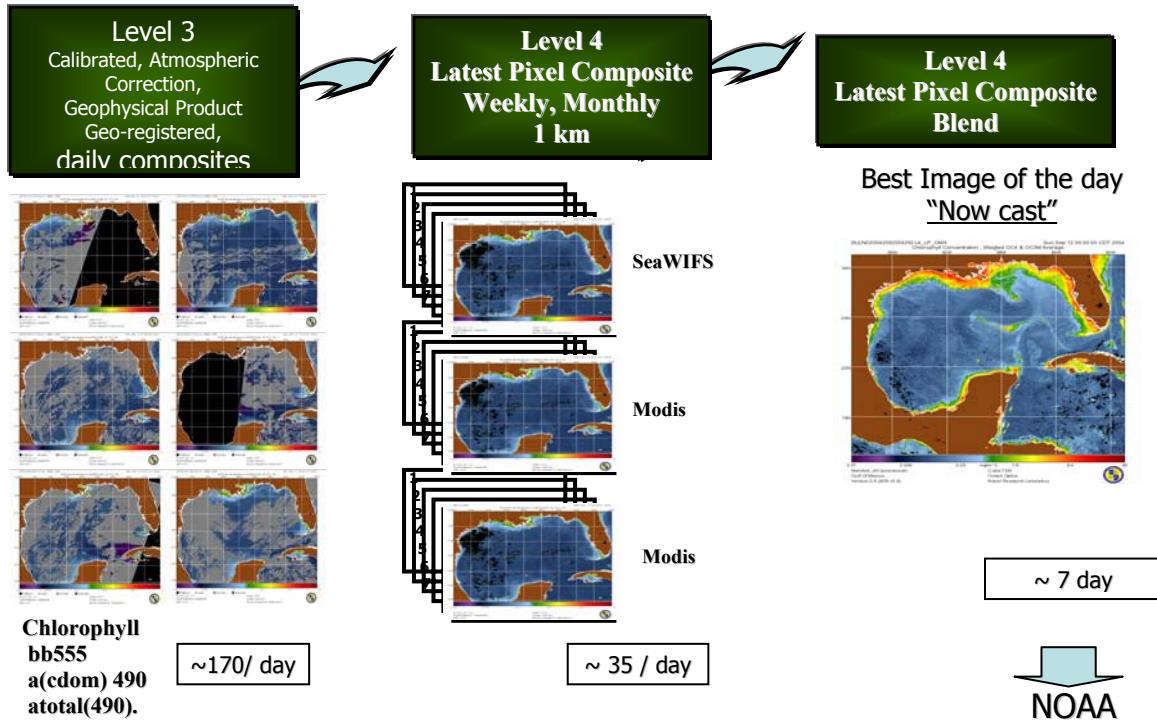


Figure 4: Distinguishing Levels of satellite processing. Compositing of ocean products to develop the latest pixel composite (LPC) representing the daily “optimum” representation of the ocean products to reduce the limitation with cloud cover. The number of products is illustrated only for the chlorophyll product. There are over 426 products per day produced for the satellite imagery.

2.3 Coastal Circulation Models

Ocean circulation models have advanced significantly for the Gulf of Mexico. The Navy Coastal Ocean Model (NCOM), developed at NRLSSC (Martin, 2000, Ko, et al., 2003, Chassignet et al., 2005), represents a state-of-the-art numerical ocean forecasting system. NCOM is a data-assimilating model with input received from both daily SST and altimeter-derived sea surface height (SSH). NCOM has been relocated for the Gulf of Mexico as part of the Intra-America Seas Nowcast / Forecast System (IASNFS). IASNFS is run daily for the Gulf of Mexico to generate a 0 - 48 hour forecast. Analyzed and predicted variables in four dimensions include a time series of SSH, temperature, salinity, and currents (Figures 5, 6). Grid spacing for NCOM is approximately 6 km. Additionally, the capability is being developed for SSH adjusted to a vertical survey datum to account for predicted inundation (corrected to orthometric height) to correlate with the United States Geological Survey, the Federal Emergency Management Agency, and the US Army Corps of Engineers mapping and hydrological products. Model forcing

includes winds and surface fluxes from the Navy Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS), eight tidal constituents, and river and coastal drainage flows. Databases are generated each day for the model outputs.

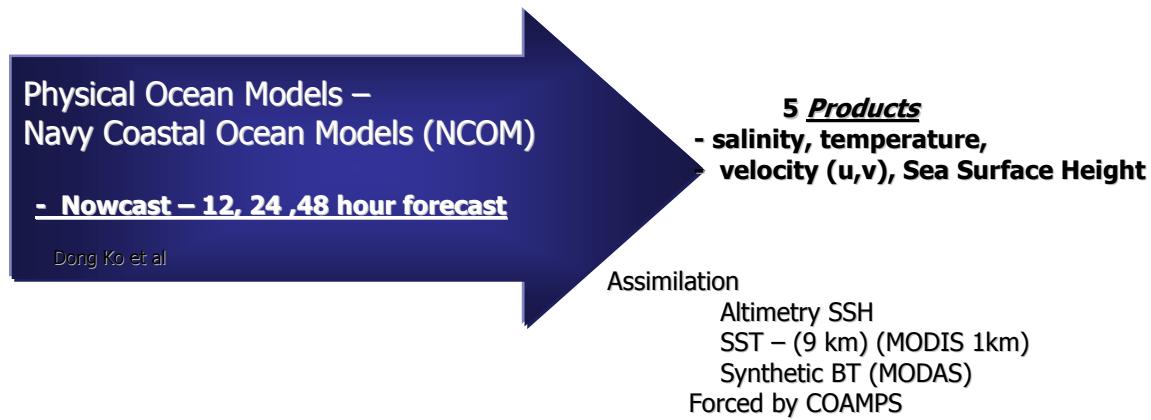


Figure 5: The IASNFS-NCOM model provides products at 41 depth levels in addition to the forecast. The physical environmental properties generated each day total ~900.

Coastal Forecasting

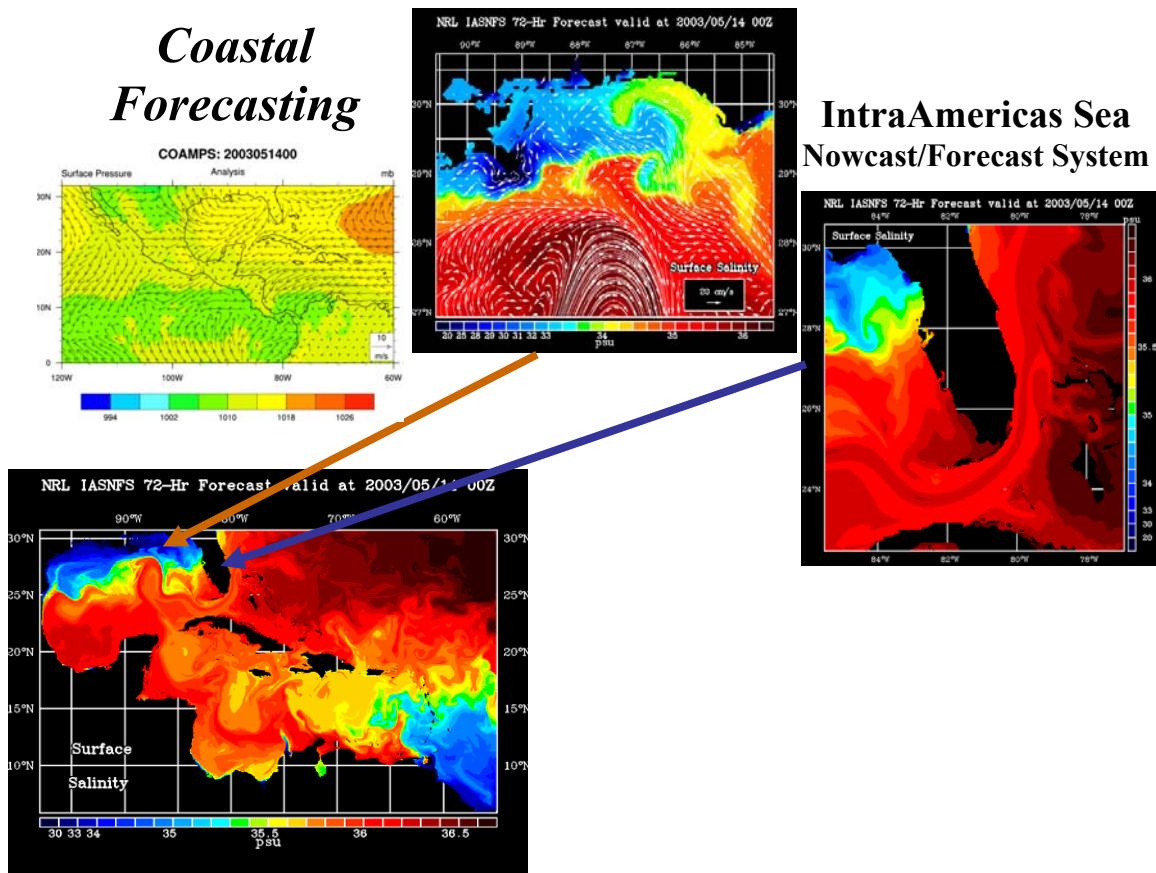


Figure 6: Examples of the IntraAmericas Sea Nowcast Forecast System (IASNFS). Model is forced by COAMPS winds at 8 km spatial resolution to deliver physical properties of the Gulf of Mexico. The larger domain of the IASNFS is shown in the salinity field (lower left) and includes the Caribbean, Gulf of Mexico, and the Bahamas. The model is forced with large scale COAMPS winds (upper left). The spatial resolution of the IASNFS for the northern Gulf of Mexico (upper right) shows the 72 hour forecast of the salinity field with the surface currents. Present river inputs to the IASNFS are based on monthly climatological discharge for ~50 rivers in the Gulf of Mexico

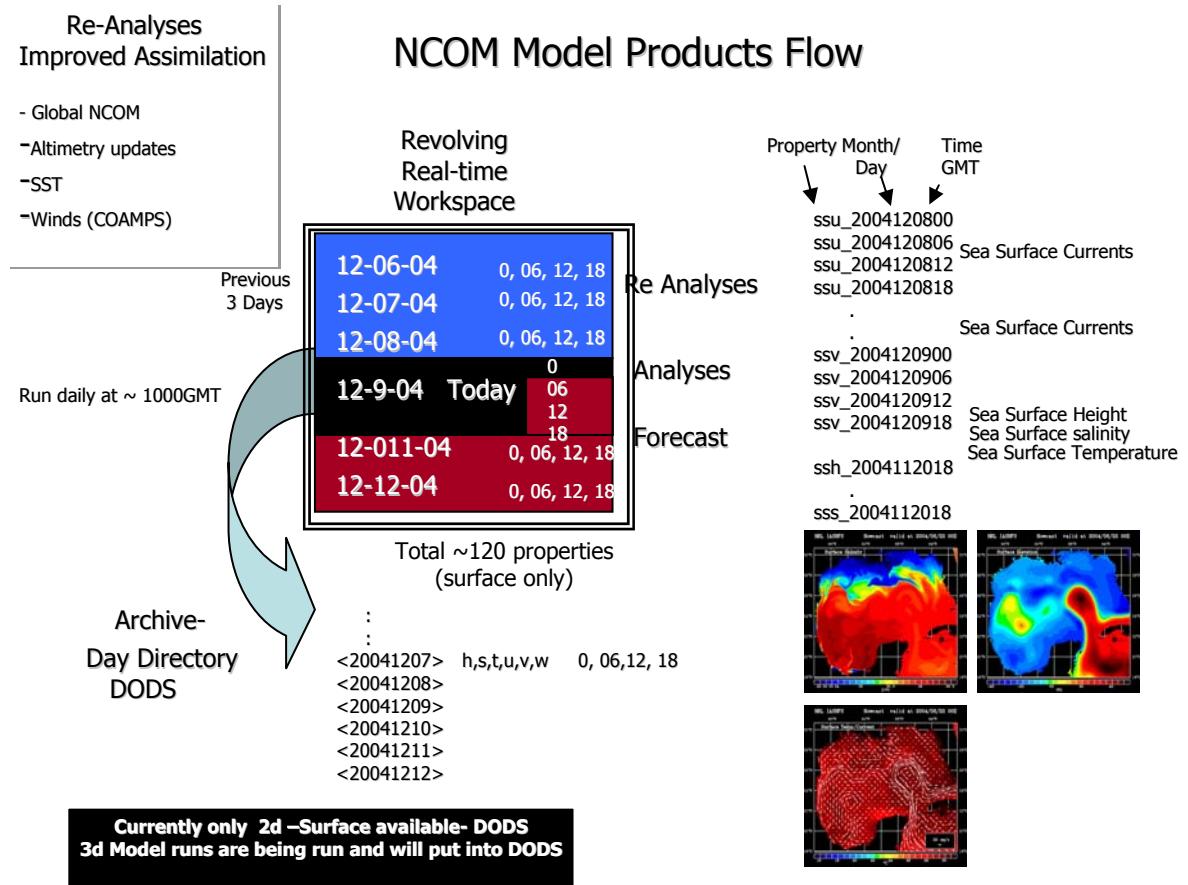


Figure 7: Updates to the IASNFS are performed daily. The update to the hindcast, nowcast and forecast are performed daily to provide an optimum representation of the physical environment.

The IASNFS runs daily with real-time inputs of satellite altimetry, SST and winds (Figure 7). The model is run for 0000 GMT each day and provides forecasts of the 0600, 1200, and 1800 for today and the next 2 days. Also, the SSH fields from the altimeter for the previous 3 days' hindcasts are updated on a daily cycle.

1.4 Merging Satellite Products and Circulation Products

The fusion of satellite image products with numerical models provides a new capability for monitoring the coastal ocean. Satellite imagery alone is not often adequate to monitor ocean conditions. Added context is required to provide additional information so that satellite imagery may be better understood. For example, the added information

of ocean circulation provides an invaluable capability to interpret satellite ocean products. A major focus of this project has been to provide a real-time, long-term data stream which, with data fusion and display enhancements, will provide a monitoring capability for making coastal decisions. This project's intention is to help the coastal managers effectively "use" these products for decision processes. This extends beyond just making the data available and requires direct interaction with the users in order to provide an integrated product. Data fusion techniques assist in the use of these data for developing an ocean weather capability.

Data distribution of all project ocean data is through the OPeNDAP server. All satellite products and ocean model forecasts are available on a daily basis through the OPeNDAP server. These data are readily available for integrating and assembling into fused ocean products (Figures 8, 9). For example, a MODIS chlorophyll image alone does not clarify the locations of major ocean currents and the locations of rings and eddies. However, when combined with the circulation and physical properties, the locations of chlorophyll fronts and eddies can be closely linked to major physical processes. The ability to recognize the response of physical and biological processes is significantly improved. This merged product and the locations of biological and salinity fronts are available on a daily basis to NOAA and to coastal managers.

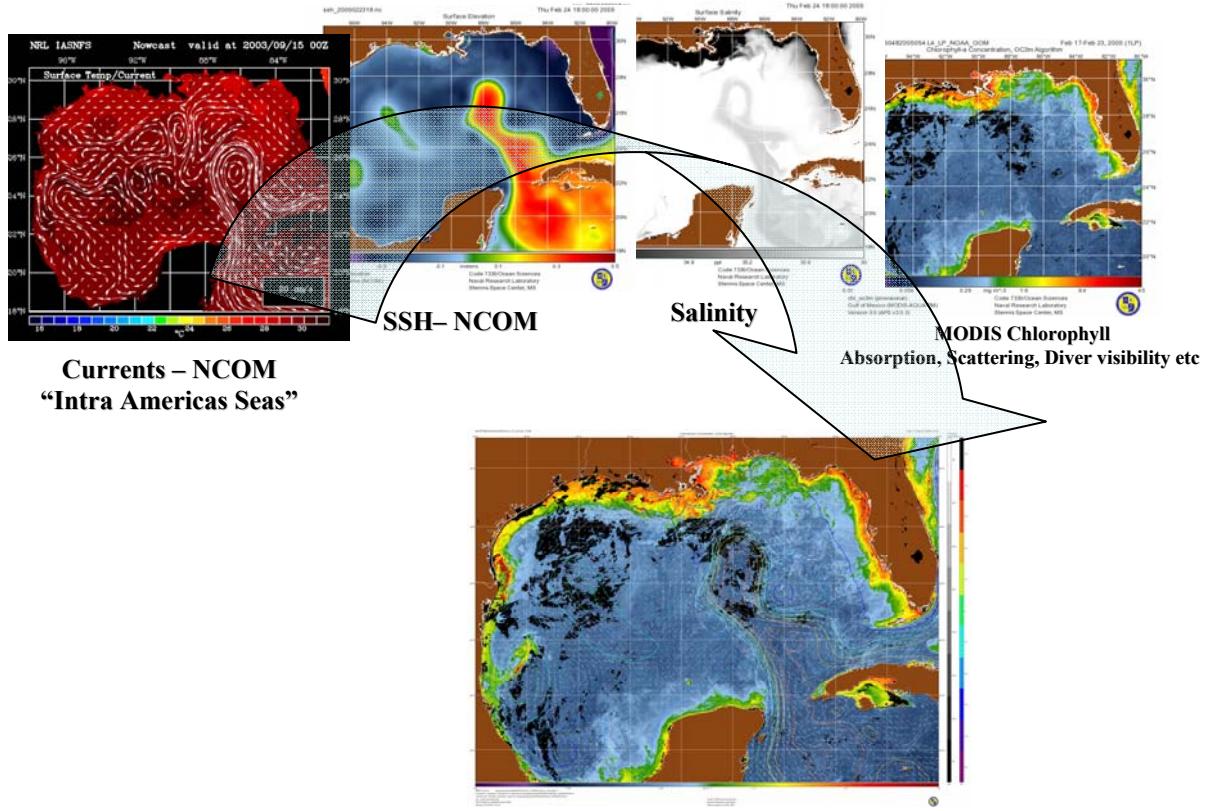


Figure 8: The fusion of the IASNFS and the MODIS products provides a realistic representation of today's "OCEAN WEATHER". The surface current, Sea surface Height (SSH) and the model salinity combined with the MODIS chlorophyll to illustrate the location of the Loop Current, the eddy fields, and how they interact with the coastal processes. The assemblage of ocean properties from ocean models and satellite imagery into a fused product illustrates surface currents, sea surface height, salinity and chlorophyll.

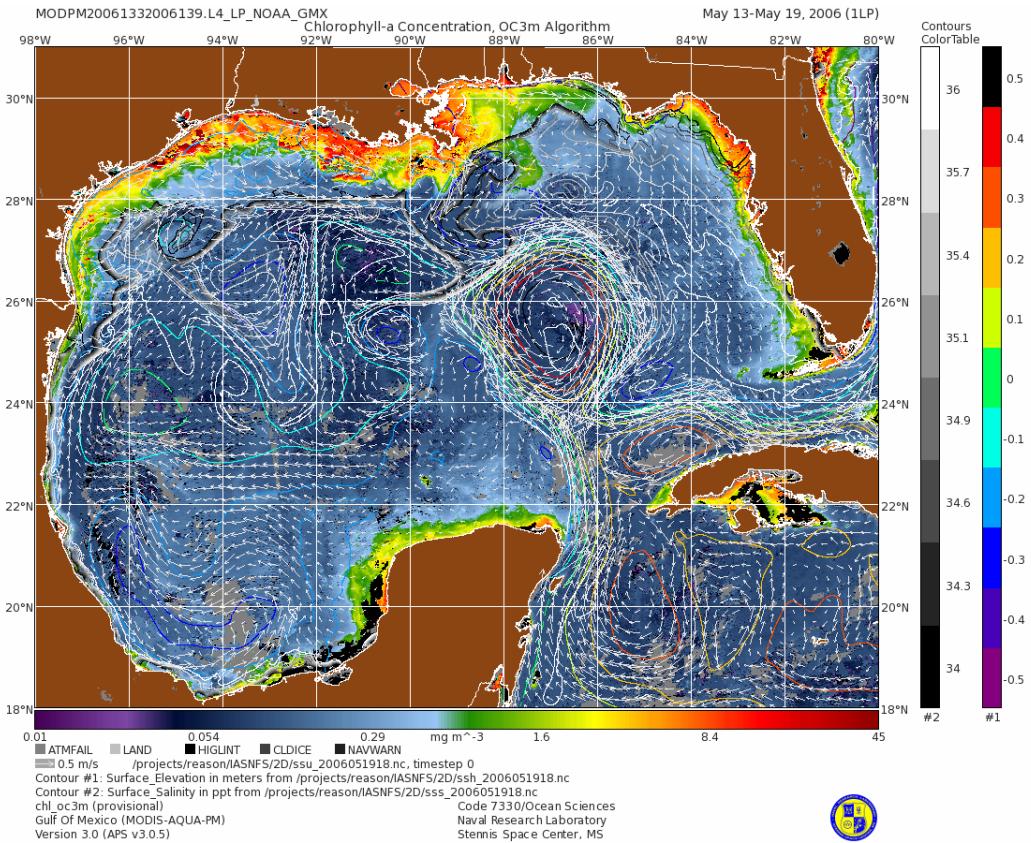


Figure 9: The fusion of the satellite imagery and the numerical model illustrates the real-time capability available through the NRLSSC server. This example from May 19, 2006 shows the chlorophyll 7 day latest pixel composite from MODIS Aqua with the color scale (below). The NCOM surface currents are overlaid and define the location of the Loop Current. The sea surface height field (SSH) is shown as color contours with the color bar on the right. The surface salinity from NCOM is shown as gray shade contours with the color bar on the right. This example of data fusion for characterizing real-time ocean conditions is available every day 365 days per year.

Coastal managers require increased spatial and temporal resolution of ocean properties for coastal decisions. These scales are available through the OpenDap server. Examples are illustrated at the 1 km resolution for three coastal regions in the Gulf. The Tampa Bay, Mississippi Bight and the Texas coastline are shown in Figure 10 as examples of daily products available for coastal managers. These products are generated daily and served by NOAA to coastal decision makers.

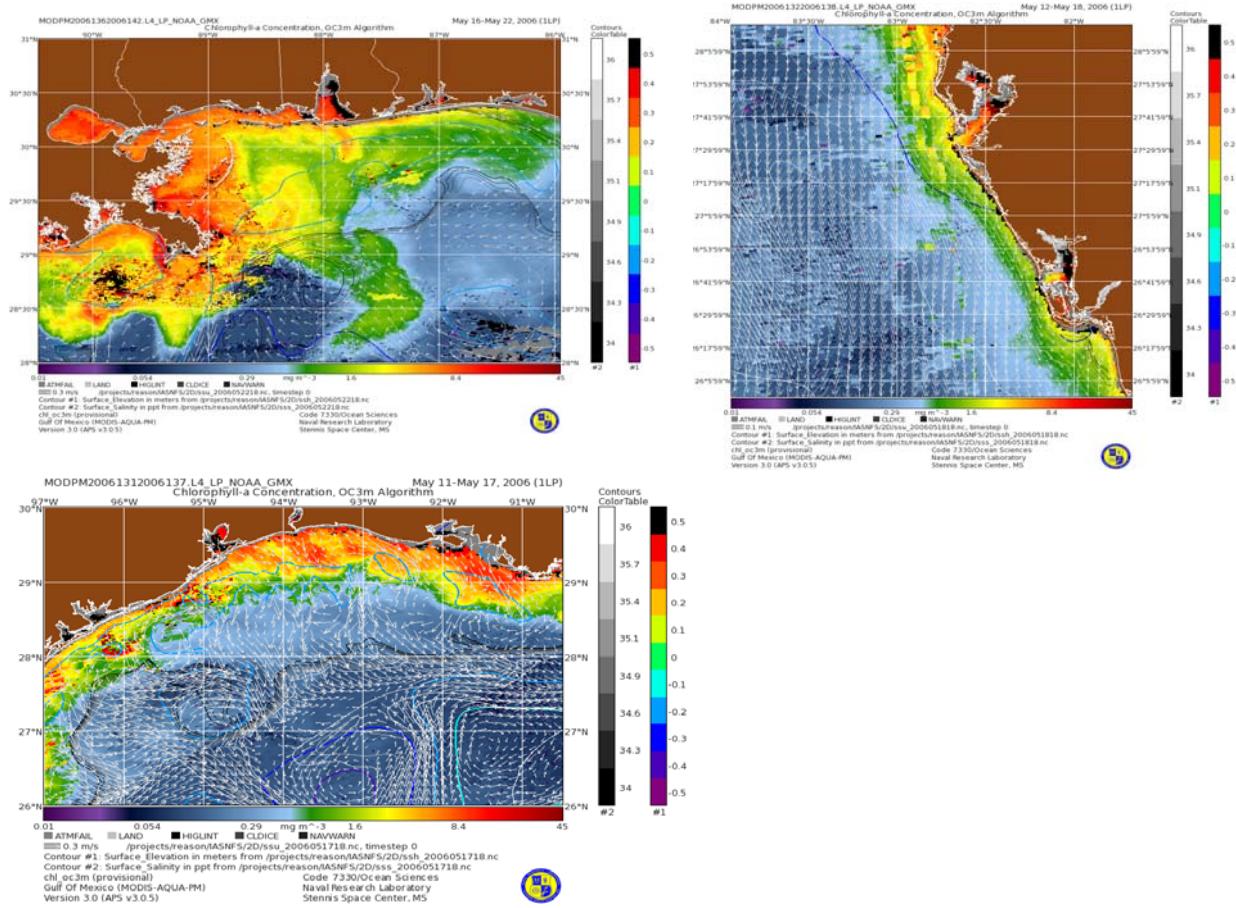


Figure 10: Detailed coastal areas for Tampa Bay, Mississippi Bight and Texas Coastal are illustrated for the daily real-time coastal monitoring capability making use of some of the NRLSSC products that are available to NOAA, NASA and ACT. Similar color scales and labels are used as described previously for May 19, 2006. These areas are examples from the animations for the NCDDC HABSOS data page that will be described later.

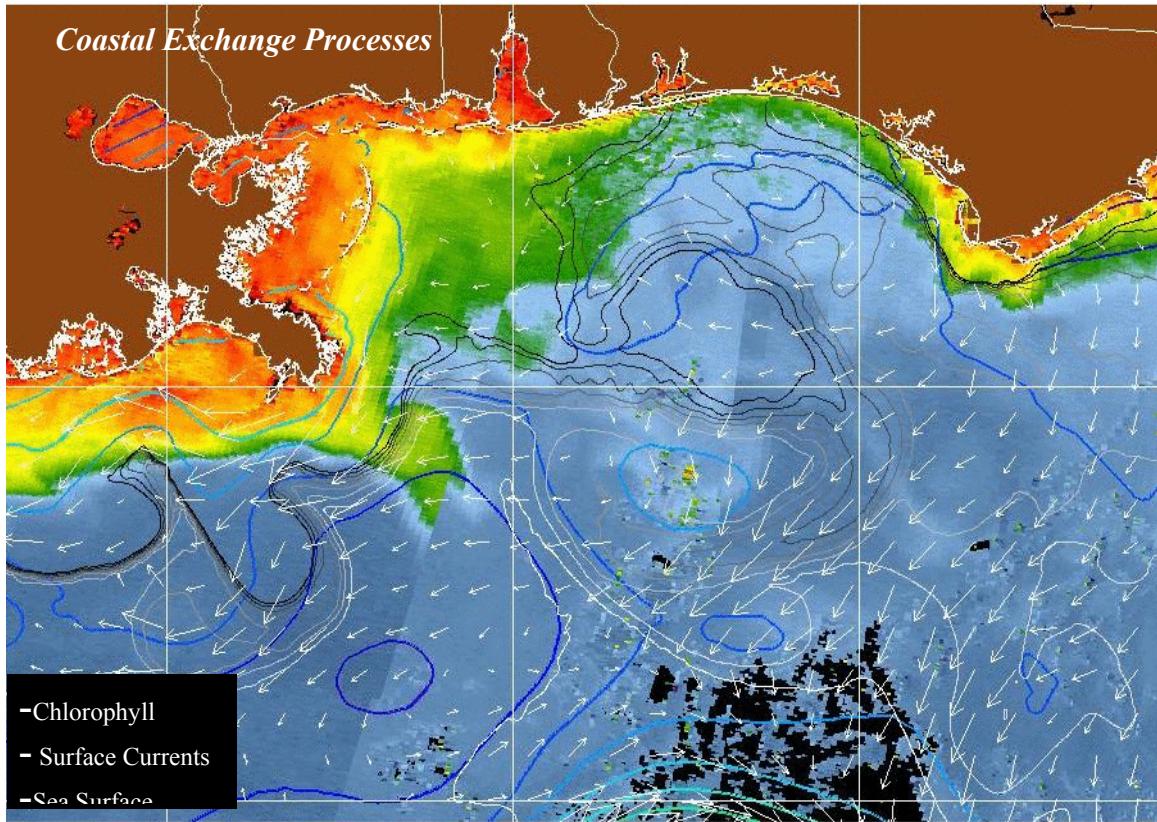


Figure 11: The real-time coastal conditions at full resolution of the 1 km imagery and the 4 km model integrated to characterize the inter-shelf of the Northern Gulf of Mexico provide a new capability for monitoring the coastal conditions. Available daily 24/7 through NOAA websites, these products enhance decision making processes. Reaching the customers is still an issue.

Presently, the resolution of the IASNFS and imagery has been at ~ 9 km and 1km but resolution is being increased at the request of coastal managers (Figure 11). The details clearly identify the locations of transition of coastal water transitions with open ocean waters in addition to the location of salinity fronts, rings, and eddies that impinge on the coast.

Note that models and satellite products are not always in agreement. This is similar to what occurs in weather forecasting and modeling. The differences between models and observations change both spatially and temporally. By examining the long time span of daily products, the locations of differences or uncertainties are in close agreement at times and other times they depart. The fusion of models and satellite imagery provides a coastal manager a degree of confidence in the data. This project intends to provide the best possible information currently available to the manager. It is recognized that this information will not be correct all of the time. As ocean models and satellite algorithms improve product confidence will evolve.

3.0 Overview of the data production, distribution and user support

3.1 Integrated Data production

Integrated analysis provides a framework for assembly of ocean properties to be provided to the customer. This project is responsible for ingestion of multi-platform, multi-sensor, multi-variable data sets into automated processing systems used for data fusion; such an approach allows users to analyze across data sets and create products from NASA and non-NASA earth observing systems, model data, and *in situ* observations.

The integration of satellite image products with numerical models provides an extended capability to understand and monitor the coastal ocean. All of the data are available as daily products on the OPeNDAP server with an added forecast capability from ocean models. These data are readily available for integrating and assembling into fused ocean products.

3.2 Satellite and Model Data Architecture at NRLSSC

For seamless integration and overlay, the satellite and model databases are in standard data formats. The target data formats for this project are based on current archiving formats as follows: satellite imagery within the data base are stored in Hierarchical Data Format (HDF), and the ocean model output are archived in the data base in Network Common Data Format (NetCDF).

The program is producing approximately 426 satellite ocean properties and ~900 physical ocean properties per day. This is a substantial number of ocean properties to assemble and maintain. However, as new advances in the products evolve, and algorithms change and the model outputs change to meet the requests of the customers, this number will change in response to feedback. For example, the output of the mixed layer depth (MLD), intensity of the MLD, or the scattering to absorption ratio (used in HAB identification) are in the development cycle and evaluation to improve existing products. These new products are under evaluation and being used experimentally at the time of this document. A follow-on report at the conclusion of this project will detail the new products that were developed during this project.

Figure 12 highlights the program architecture that was used at NRLSSC for data flow and processing. These ocean data have been coupled with the WIPE servers located at NOAA, ACT, NRLSSC, and entered into the WIPE format. Limited access to the NRLSSC server and ACT server is provided to the NOAA Centers and NASA–Applied Sciences Program. Direct customer interface is through NOAA.



Figure 12: The Program Architecture of how products are distributed through an OpenDAP server. The research and operations link through NOAA and NASA provides a method for managers to exploit these ocean data on a 24/ 7 basis. Improved methods to enhance the products and product delivery are being addressed on individual customers.

3.2.1 Data Distribution: OPeNDAP/Distributed Oceanographic Data System (DODS) Server

The satellite and numerical model results have been assembled onto a DODS server. The NRLSSC DODS server is exclusively available to all offices within NASA, NOAA, and ACT to provide a structured conduit for the environmental data collected and processed by NRLSSC for the Gulf of Mexico. This server also provides a common and standard access point for the NRLSSC advanced products (Level 4 and integrated products) as well as NGDC compliant metadata. The DODS server is now accessed daily by NCDDC for integration into their ArcIMS web server for real-time data of the Gulf of Mexico.

OpenDAP has the following capabilities (also Figure 13):

- Automated request for specific data sets can be set to the client.
- Specified areas/ sub areas can be readily identified within the Gulf of Mexico data sets.
- Metadata data available to the client of each variable.
- Once the data format is identified to the OPeNDAP server, the data can be reformatted to a number of user requested data formats. For example, satellite data in OPeNDAP are integrated in HDF format but the client can request the data output in ASCII.
- All data are navigated with locations.
- As new, improved data are developed by the research community, they are entered into the OPeNDAP server and immediately available to the user. Similar programs used to retrieve, display, and overlay the data can be used for all new products immediately.
- A number of software programs are readily available that can already link into OPeNDAP servers. These include Matlab, WIPE, and Feret.
- OPeNDAP software is readily available for general applications.

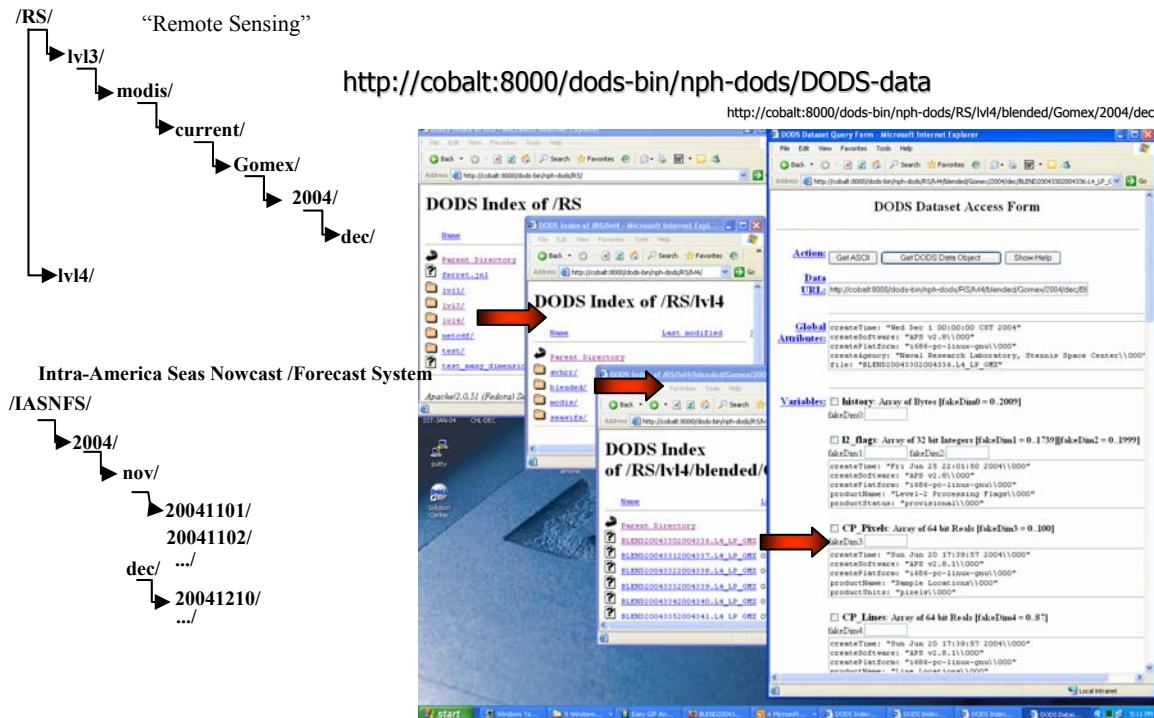


Figure 13: An example of the data directory structure for the OPeNDAP data server.

3.3 Application to Coastal Management

The Gulf of Mexico demonstration program developed an engineering system for 1) establishment of automated production of satellite products and numerical models, 2) operational datastream for ocean products in the Gulf of Mexico for use by coastal managers, and 3) delivery of a real-time ocean nowcasting/ forecasting system to NOAA. The utility of these ocean data were then directed at specific coastal decision making opportunities in the Gulf of Mexico to provide new benchmarking assessments and activities. This was performed by coupling data availability with several federal partners and state agencies.

Three specific applications of ocean products for coastal decision makers are recognized in this report. Note that developments evolve as new customers and utilities are realized. At the time of this report the project is approximately halfway completed and that follow-benchmarking activities are in process and will be completed. Three benchmarking applications have been identified for review:

- 1) Integration of real-time ocean products into NOAA-NCDDC's HABSOS information portal;
- 2) Development of improved anomaly fields for improved assessment of bloom identification for the NOAA HAB Bulletin; and
- 3) Improved decision-making capability for the Mississippi Department of Marine Resources for monitoring shellfish beds and reefs.

The initial focus of the benchmarking efforts for the first two years has been on HABs, which occur regularly in the Gulf and represent a series impact on economic and commercial issues. HABS have been a growing concern in the Gulf and have spawned considerable interest at national and state regulatory agencies. Accordingly, the gap between advances in research and utility in operations is increasing. Real-time nowcasting and forecasting of ocean conditions from the merged satellite and numerical models available from this program provide a needed capability currently unavailable.

Advances and improvements to NOAA HAB detection and forecasting capabilities is an exciting new capability brought about from this program. Therefore, this demonstration is tightly linked through extensive coordination with NOAA centers to provide new advanced demonstration products on a real-time basis.

3.3.1 - Harmful Algal Blooms Observing System: (HABSOS)

This project coordinates with NOAA programs to enhance their capability to support the Harmful Algal Blooms Observing System (HABSOS) and to provide additional guidance and new products to the NOAA HAB Bulletin. The HABSOS pilot project is a proof-of-concept demonstration of an integrated information and communication system for managing HABs data, events, and effects. The HABSOS pilot project is initially focused on the Gulf of Mexico but will ultimately expand throughout the coastal United States

The NOAA NCDDC web portal obtains real-time data of the ocean conditions from the NRLSSC servers on a continual 24 hr basis (<http://www.ncddc.noaa.gov/habsos/Mapping/>, Figure 14). The HABSOS site provides real-time and historical ocean data for managing HABs. The site is open to the public and provides a pathfinder for distributing research and operational data from this NASA project to coastal managers. The HABSOS site represents an easy method to overlay a subset of environmental data available from the NRLSSC server (Table 3). Currently, NOAA is only extracting about 9 satellite products of the latest pixel composite which remove clouds and 16 products from IASNFS - NCOM.

Table 3. Satellite image and model products available on the NRL-SSC OPeNDAP server. These products are only a subset of the available data from the OPeNDAP server at a reduced resolution because of the limitations of the ArcIMS server operating on the web. As effective new products and requirements are recognized by coastal managers and developed, they will be added to the HABSOS server.

Satellite Imagery	Ocean Data MODEL – NCOM	Meteorlogical Data
MODIS – 250m Turbidity (MS Bight)	Current from Buoys	Winds from Buoys
MODIS – Total Absorption (443) Latest Pixel Composite	NCOM – Surface Currents Nowcast, 24,48, 72	Winds from QuickScatt
MODIS – Absorption (412) CDOM Latest Pixel Composite	NCOM – Surface currents Speeds 24,48, 72 h forecast	NWS – Air Temperature 24, 48,72 Forecast
MODIS – Backscattering Coefficient 555 Latest Pixel Composite	NCOM – Surface Heights Nowcast, 24, 48,72 forecast	NWS – Precipitation 24, 48, 72 h forecast
MODIS – Absorption (443) of Phytoplankton Latest Pixel Composite	NCOM – Surface Salinities Nowcast, 24, 48, 72 h forecast	
MODIS – Surface Chlorophyll OC3 – Latest Pixel Composite		
Latency of the Image Latest Pixel Composite		
MODIS – Sea Surface Temperature (Day and Night) Latest Pixel Composite		

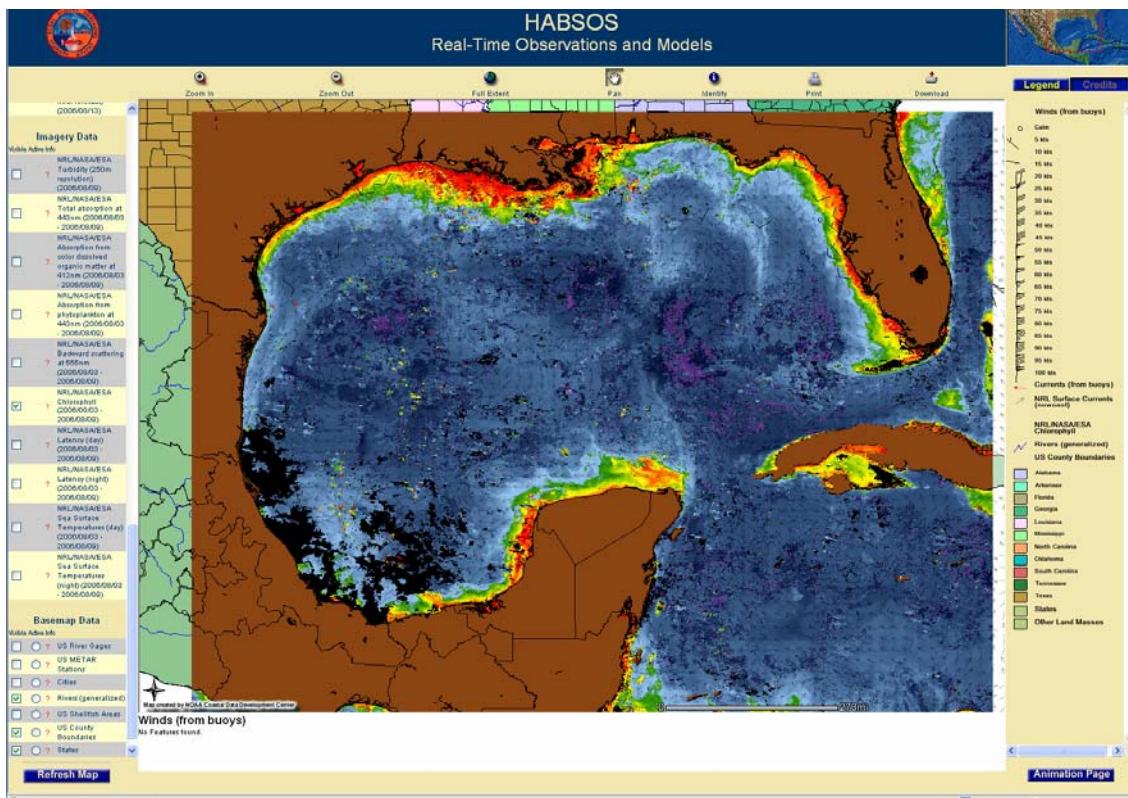


Figure 14: This example from the NCDDC HABSOS web site illustrates the real-time satellite and numerical model data available through the NRLSSC server. On the left side of the base GIS map, available oceanographic and meteorological layers are displayed. The oceanographic layers illustrate the satellite and models outputs. The example of the 7 day latest pixel chlorophyll composite with the surface currents identifies a new ocean monitoring capability. Black areas are clouds.

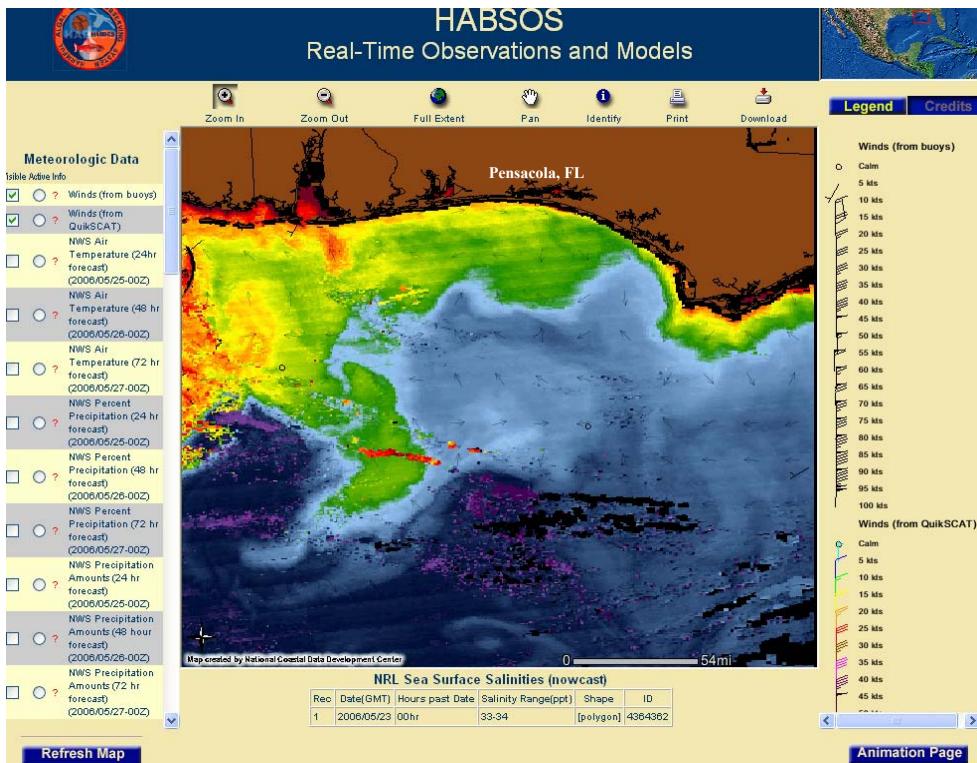


Figure 15: The real-time NCDDC HABSOS web page illustrates the CDOM MODIS product with the surface currents for the Northern Gulf of Mexico. Note the potential of satellite data product overlay on the left side. The example illustrates the cyclonic eddy of clear (light blue) water offshore of Pensacola and its influence on the coastal waters.

These examples from the NCDDC HABSOS web page are static snapshots of daily ocean conditions. An added capability for monitoring ocean conditions is to develop animations of the weekly sequence of the ocean conditions. This is similar to weather animations shown on local television weather channels. Animations are viewable through a web site link at the bottom right of the HABSOS page (Figure 15). The animation sequence provides a new capability to monitor conditions for the last week. NOAA and NRLSSC decided to automate this procedure for three regions of NOAA importance for monitoring Gulf of Mexico HABs activity. These include the Tampa Bay region, Mississippi Bight, and the Texas coast (Figure 12). The HABSOS web portal for providing ocean conditions for the Gulf of Mexico began operations on June 2005 and has continued to the present on a 24/ 7 operation. The capability provides a unique capability for coastal managers who need the latest ocean conditions in the Gulf.

3.3.2 Harmful Algal Blooms Forecasting: Application of New Residual Products

Creating the Harmful Algal Bloom Bulletin within NOAA currently requires significant time. The final product requires gathering information from multiple sources (SeaWiFS

satellite data and surface wind observations), making data cuts, adding analyses and text, and formatting for output. Present added features are for the ACT WIPE to provide automated capability to enhance the generation of this product. The new application will serve MODIS, *in situ* data, and ocean model predictions, automatically make data cuts and create an output in the format required.

The present Bulletin is based on analyses of satellite chlorophyll products (in addition to wind vectors) and interactive user analyses. The present chlorophyll algorithms used are empirical algorithms of a ratio of channels (modifications of OC33 and OC4). The current procedure for using satellite products is to examine anomalous coastal chlorophyll fields. This is performed by determining the residual between the current chlorophyll image (daily image) and a climatological two-month running mean that ends two weeks before the current image. This two-month running average of chlorophyll accounts for seasonal variability. The residuals of the chlorophyll field are identified as possible HABs. The present NOAA Bulletin uses SeaWiFS data for chlorophyll analyses; MODIS data are in evaluation. The satellite chlorophyll product is not always representative of a harmful algal bloom and can represent a region of elevated phytoplankton concentration or other optical components. In coastal areas, water constituents such as CDOM, detrital absorption, and particle scattering may influence the uncertainty of chlorophyll retrievals and, thereby, influence the anomalous / residual fields. That is, not all chlorophyll anomalies are chlorophyll and not all are HABs. Research products from the OPeNDAP can possibly be used to separate these anomaly fields and identify these areas. This demonstration identified new products that can be used to aid NOAA in identifying these non-HAB residual fields. These include residual fields from backscattering at 555 nm, total absorption at 443 nm, and detrital and CDOM absorption. The previously described QAA algorithms can be used to separate these bio-optical components and provide new capability for complex coastal waters.

These enhanced bio-optical research products and their residuals may improve the NOAA HAB Bulletin through the separation of harmful and non-harmful phytoplankton species. New bio-optical products from satellite imagery can separate chlorophyll from other bio-optical components, especially in coastal areas and provide a method to define packaging of chlorophyll per unit particle (to characterize species identification). Chlorophyll is packaged within phytoplankton and the size of phytoplankton cells provides an indicator of phytoplankton species separation. The separation of these phytoplankton species can be identified by the ratio of the backscattering to total absorption. Both of these bio-optical components can be retrieved from MODIS ocean color and can be used to provide an index of chlorophyll per unit particle. Larger ratios of absorption to scattering are expected to represent dinoflagellates, including *Karenia brevis*, the typical HAB species in the Gulf of Mexico. These indices can provide added information for determining HAB locations used in NOAA Bulletins. These residual products of scattering and absorption components are being produced as part of this demonstration project and can be compared to the standard chlorophyll residuals to identify non-harmful phytoplankton. The residual fields of these products are generated in a similar method as the chlorophyll residual field (Figure 16).

These new products are under evaluation and consideration with the NOAA HAB algorithm team (Rick Stumpf of NOS and the Coastal Services Center). The new optical anomaly products are being tested and evaluated with HAB locations and match-up sites with the chlorophyll residuals fields. These products are available through the OPeNDAP server.

This demonstration presently generates MODIS chlorophyll residuals products to compare with NOAA SeaWiFS chlorophyll residuals. Additional bio-optical residual fields are also delivered. This NASA project provides the operational HAB community readily available, new research products for application and evaluation. The demonstration rapidly prototypes new products and “short-circuits” the traditional software implementation of new complex bio-optical algorithms and their integration within satellite data processing. Typically, the process of getting new algorithms integrated, implemented and tested within NOAA operational ocean-color processing requires several years. The new products available through the OPeNDAP server can be readily tested and evaluated to determine if they should be integrated into operations. This saves time and funding and provides an improved capability for integrating research products into operations.

The example of the optical residual fields is only one example of how new products can be better integrated into operations. The extensive real-time products of the Gulf of Mexico is not available at NOAA operational centers; this pilot demonstration identified future capabilities for operational centers such as NOAA.

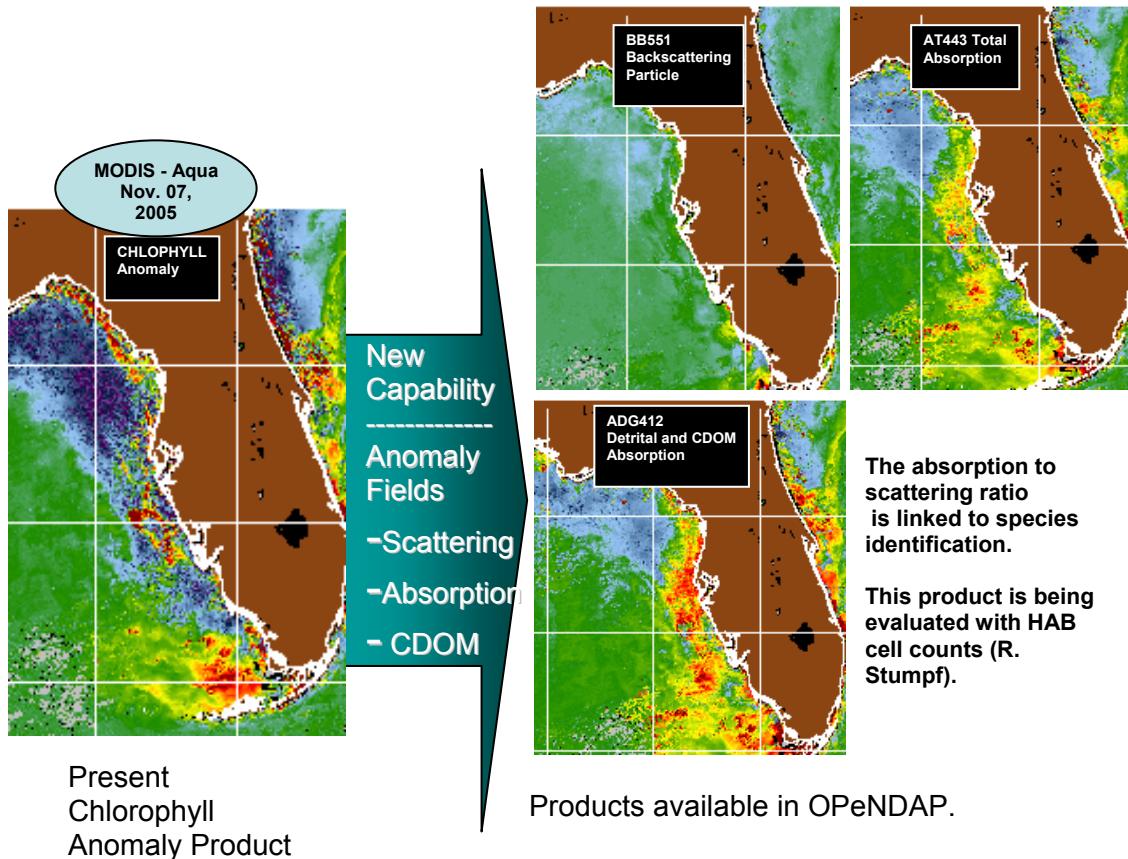


Figure 16: Improved products to support HAB decision making in the Gulf of Mexico. New anomaly fields of the bio-optical properties from MODIS can be used to support the NOAA HAB Bulletin. These products are under evaluation by NOAA.

3.3.3 Applications for Shellfish Monitoring by the Mississippi Department of Marine Resources

Coastal managers continually request near real-time assemblages of data to support their management activities. These data may be used to increase the efficiency, effectiveness or accuracy of their activities as well as assess spatial and temporal changes in coastal conditions. Forecast products can be used to aid decisions for both planning and monitoring activities as well as regulatory decisions (e.g. closing an oyster reef). The Mississippi Department of Marine Resources (MDMR) is the agency responsible for regulating marine resources for commercial and recreational activities within the State of Mississippi. For example, one of MDMR's key responsibilities is determining shellfish bed closure due to high levels of fecal coliform contamination. This decision-making process uses an extensive water sampling program coupled with river gauge monitoring. The present suite of real-time ocean products from satellite and circulation models that

was developed and provided through this NASA project was linked with MDMR requirements to provide a greatly improved capability for managing its coastal zone.

Through a Memorandum of Agreement with NOAA and a series of joint meetings with NASA, NOAA and NRLSSC scientists, the MDMR agreed to evaluate the products provided by this study for both finfish and shellfish management activities. DMR provided NRLSSC and NOAA a list of data requirements for the evaluation. These included the following:

1. *Estimates of daily, satellite-derived short-wave radiation at the sea surface.* These estimates of photosynthetically available radiation (PAR) fields are used to determine the degradation of fecal coliform in surface waters and the extent and duration of water contamination.
2. *Locations of coastal salinity gradients.* Discharge of local rivers is primarily responsible for fecal coliform presence in coastal waters. The dispersion of fresh water from rivers into estuaries and the Mississippi Bight determines if shellfish beds should be closed. Locations of these fresh water plumes is required to aid in the ship sampling programs and provide adaptive sampling based on nowcasting and forecasting of salinity distributions.
3. *Locations of turbidity fronts and sediment fallout areas in the Mississippi Sound.* Sampling and monitoring efforts benefit from locating and tracking turbidity fronts in the Mississippi Sound. Turbidity front locations determine the extent of freshwater plumes and provide an estimate of the resident time of river water in the Mississippi sound. Turbidity fronts are used to guide ship water sampling strategies, used for contaminant tracking, and determine fish stocks (water turbidity provides an estimate of the subsurface light field). Estuarine-dependent and coastal fish species production are enhanced in the vicinity of riverine discharge. Larval fish densities are highest at the associated turbidity fronts. Tracking overall turbidity in Mississippi Sound is important for monitoring the health of submerged aquatic vegetation (SAV), a large proportion of which has been lost in the Mississippi Sound in the past 30 years. MDMR monitors sediment fall-out areas for changing patterns of deposition and possible impacts from trawling and dumping of dredge spoils
4. *Estimation of shelf water ventilation for the area south of the barrier islands as an indicator of summer hypoxic events.* Oxygen content and the flushing times of coastal waters on the shelf are indicative of ecosystem health. Ship measurements are used to assess hypoxic conditions along the coastal. Locations of stagnant water masses on the shelf help identify possible hypoxic regions and establish a guide for ship sampling. Ventilation of coastal waters can result from strong onshore – offshore wind events and associated currents or the movement of large offshore rings and eddies migrating onto the shelf. Hypoxia conditions can occur when Mississippi River waters are advected to the east and onto the shelf.
5. *Forecasting of surface currents and water properties within coastal waters.* The forecast of currents and waters masses provide MDMR the capability to determine the

locations of contaminated waters and their movement into a shellfish bed or on a beach.

These MDMR requirements are used for enhancing the real-time ocean products being delivered through the OPeNDAP server. These 5 requirements were examined by the NRL research scientists to determine how satellite products and ocean models can provide real-time capability for DMR. New algorithms were implemented to address these requirements:

- a. A PAR algorithm was implemented into the MODIS satellite processing and is now available on the OPeNDAP server.
- b. A new salinity algorithm for MODIS ocean color products was developed based on the link between the CDOM and salinity.
- c. The MODIS 250-m beam attenuation coefficient product was enhanced using an edge detection algorithm to locate turbidity fronts. This product was sent to MDMR and NOAA to aid in ship sampling. These products are now part of the MDMR web page.
- d. The real-time rings and fronts from satellite imagery and ocean models are used to examine ventilation of shelf waters. The real-time data provide estimates of water mass identification on the shelf.
- e. Forecast currents and water masses on the shelf are available for predicting advection processes on the shelf. The satellite water mass classification product (based on different absorption properties from CDOM, detritus and phytoplankton) is being evaluated to determine the residence time of surface waters.

The Oyster Reef Management in the Mississippi Sound is being enhanced by the use of real-time integrated ocean products from satellite and numerical models. High levels of fecal coliform can contaminate oysters and require oyster bed closures by the MDMR. Fecal coliform concentrations can be correlated to relative solar radiation, cloud cover, SST, river runoff (turbidity), and salinity. NRLSSC provides MODIS-derived estimates of solar radiation, SST, and turbidity as well as salinity estimates (Figures 17, 18, 19). NOAA NCDDC provides these data to MDMR for use in their fecal coliform decision tools.



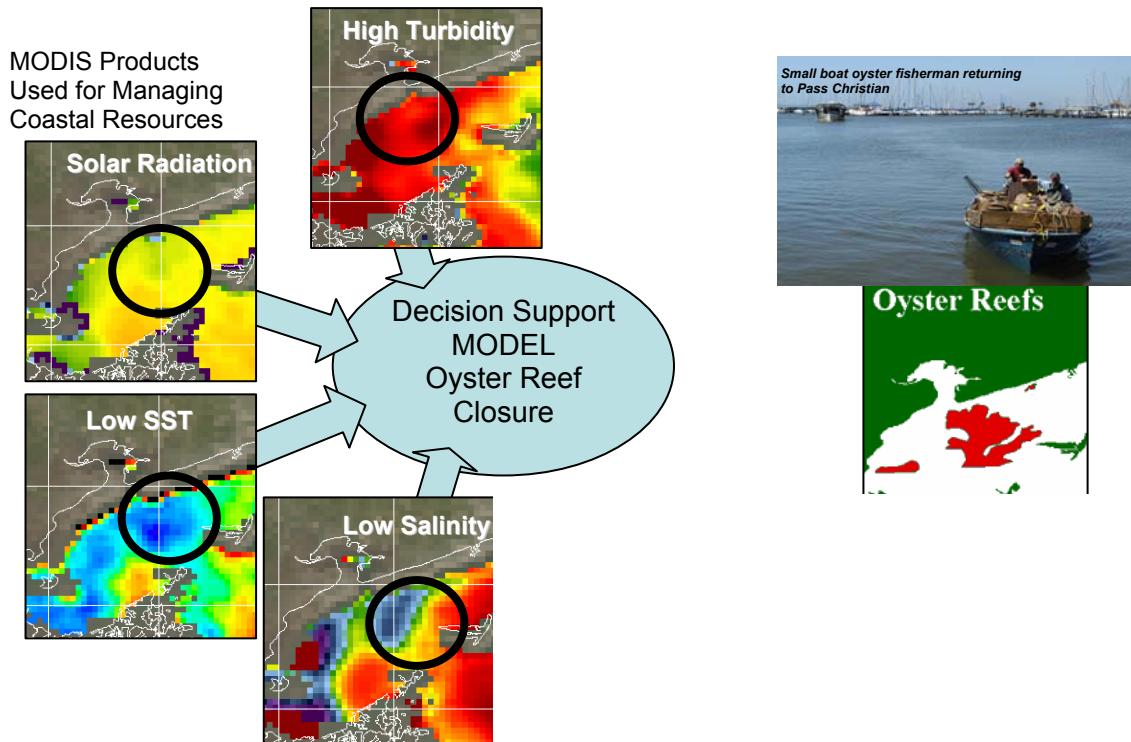


Figure 17: New ocean products from MODIS are used to support MDMR decisions on when to close shellfish beds. Monitoring the coastal environment with MODIS products provides useful methods to determine health hazards. New salinity and PAR algorithms are available daily through the OPeNDAP server and distributed by NOAA.

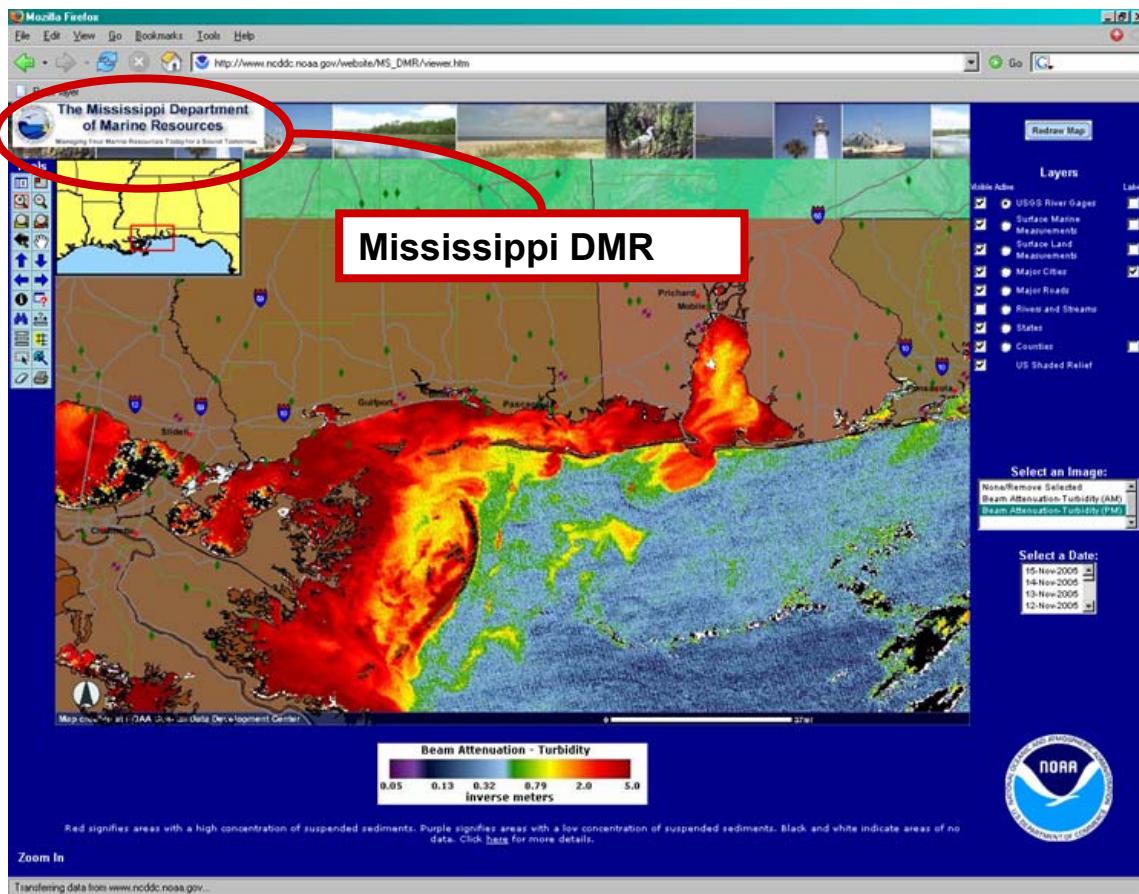


Figure 18: A NASA product example from the MDMR website. Conditions in the Mississippi Bight are illustrated by the 250-m MODIS “turbidity” products. The imagery provides a new capability to monitor coastal conditions.

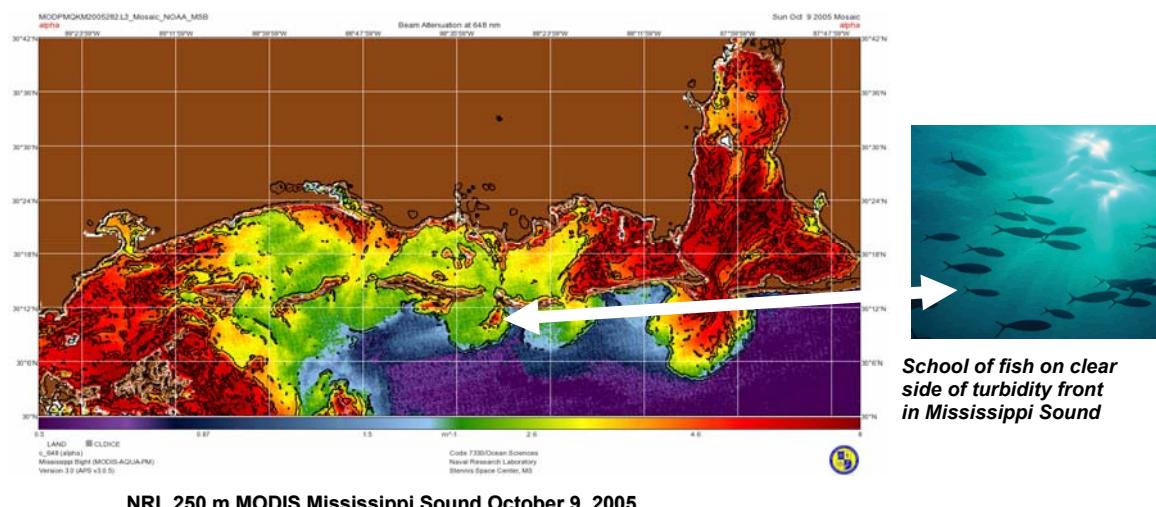


Figure 19: A new product developed for MDMR to define regions of turbidity regions. This product developed with NOAA NCDC, NASA and NRLSSC enables coastal monitoring with MODIS and numerical model data. The turbidity products enable MDMR to perform efficient *in situ* monitoring for identifying health hazards and potential shellfish bed contamination.

4.0- Metrics for Integrated Data Analyses for the Gulf of Mexico

Metrics used in this project examine the effectiveness of the products generated to support the decision-making process of NOAA and their users. Two methods are used to examine project effectiveness:

1) Developing new products and data exchange infrastructure to support specific requests from NOAA and coastal managers, and

2) Assessing the volume of products and data exchanged from the NRL-SSC OPeNDAP server.

At the request of coastal managers and NOAA, many new products were developed for this project:

- 1) coastal salinity products from MODIS ocean color,
- 2) surface light field from MODIS ocean color,
- 3) turbidity frontal product from MODIS 250 m imagery,
- 4) metadata for all the NRL products (~200),
- 5) development of animated ocean products and delivery to NOAA,
- 6) increased spatial resolution nest of circulation models in the northern Gulf of Mexico,
- 7) development of the anomaly field of bio-optical products for NOAA HAB detection and forecasting,
- 8) three-dimensional coastal chlorophyll fields (under development), and
- 9) chlorophyll distribution forecast product (under development).

The second metric examined the data volume of distributed products. NRLSSC continues to support an OPeNDAP server as the first-tier access point to NRLSSC MODIS satellite and Navy Coastal Ocean Model products for the Gulf of Mexico. The volume of data exchange was computed to assess the metric of products distribution and its utility to the customer (*see the following chronology*).

1. Following the originally proposed project data architecture, the NRLSSC OPeNDAP server is only accessible by *.mil, *.noaa.gov, *.nasa.gov and *.actgate.com domains.
2. As of February 1, 2006, 1226 unique and derived satellite data and model output fields are placed on the server each day as products.
3. A single day represents 4.8 GB of storage.
4. NOAA NCDDC is the most regular and largest volume user of the NRLSSC server.
 - a. NCDDC supports several interfaces to the NRLSSC data (*e.g., Katrina Impact Assessment, Mississippi Department of Marine Resources, and the HABSOS sites – <http://www.ncddc.noaa.gov>*)
 - b. FGDC compliant metadata are available for each product or product family on the NRLSSC OPeNDAP server for use by NCDDC.

- c. NRLSSC data are provided in geolocated format for use in GIS web-based systems.
- 5. Other government users of the server include USCG, USJFCOM, and NOAA National Data Buoy Center.
- 6. ACT WIPE server statistics are not included in these metrics.

The metrics show that a significant number and volume of “research” products are being developed and are available to operations (~140 gb /month). Of this, only about 3% (4 gb) is accessed by several (limited) users such as NOAA. The distribution of these products for coastal decision making is even more restrictive. This highlights the issue that research products will always outnumber operational products. However, with effective use of specialized products, a significant contribution to operations can evolve. For example, the utility of a single satellite image in a coastal zone provides invaluable guidance for effective ship sampling and significantly improves the capability for monitoring spatial variability of fecal coliform and HABs. Improved methods for evaluating advanced technologies such as new ocean products from ocean color satellites and numerical models available in real-time from this effort elucidate how operations can and will be performed in the future.

4.0 Benchmarking Gaps and Recommendations

The benchmarking process for this demonstration project is challenging in that almost nothing existed before the project. The present assemblage of satellite products and numerical modeling available as a 24/7 real-time *ocean monitoring and distribution capability* does not exist for US coastal waters. Therefore, we have had to rely on metrics, such as those described above, to identify the gaps and data utility of the present demonstration. It is clear from the communication and response of NOAA centers and from environmental and disaster management authorities, that the OPeNDap and products delivered by this project have become mainstreamed into the coastal decision-making process. NOAA and its customers integrate these real-time products into their websites and use them to direct their field programs and sampling strategies for monitoring coastal resources.

Moreover, with increased awareness of specialized customers needs such as the MDMR, improved products can be established to address product effectiveness. However, there are identified gaps which can and should be addressed:

- 1) The methods for customer feedback are not clear. How ocean products are used, or can be used and the requirements of the customer need to be identified to the research community. Direct feedback or evaluation of the present real-time products is not clear.
- 2) The customer interaction with real-time ocean data requires an improved interface. A simple interface will provide a sequential training of new ocean products. Training customers to use new products and while increasing complexity as the customer becomes familiar with the products and product credibility should be established. The products available on the OPeNDAP server are complex and require improved customer awareness.

- 3) Animated sequences of ocean products best illustrate the dynamic coastal environment . Ocean weather animations provide coastal managers a heightened awareness of coastal processes. Such animations, including forecasting capability, are available through the OPeNDAP but have not been exploited.
- 4) The integration of this demonstration with NOAA operational groups requires a more formal process for identifying transition products. A transition team is required to develop the methods and protocols by which products become operational, identify products from the OPeNDAP server that should be made operational (not all products should make it to operations), and develop a “rapid” transition architecture whereby a method is established to quickly move research products into NOAA operations.
5. The products and capability of this demonstration in the Gulf of Mexico have not been adequately announced to commercial and public coastal managers. The capability must be “sold” to managers and publicly demonstrated. Presentation of this new capability must be done at both science, applications and user meetings. It is recommended that several technical and application briefings be developed based on the results of this project and that representatives from NOAA, NASA, NRL-SSC, ACT, and MDMR, use these briefing materials as part of their programs.
6. Awareness of this demonstration in the Gulf of Mexico should be made through national publications, e.g., journals of satellites exploitation, GIS data exchange or coastal management.

5.0 Summary and Conclusion

A unique capability for the Gulf of Mexico has been established to demonstrate the utility of NASA data and modeling products for application in decision support tools of Federal partners. This project demonstrates a 24/7 ocean monitoring capability that pioneers methods for supporting Coastal managers requiring real-time ocean conditions in the Gulf of Mexico. The effort enables new state-of-the-art ocean monitoring and forecast capability using NASA satellites to be evaluated and tested in operational and decision-making scenarios. This demonstration project initiates a rapid transition process from research to operations. Rapid prototype products can be quickly evaluated, tested and assessed for operational capability before they are integrated into operations.

This new capability establishes a precedent for the US commitment to evolving coastal management systems (i.e., Integrated Ocean Observing System). The demonstration merges NASA satellite data with numerical models to enhance the monitoring, assessment and prediction of the coastal environment and to provide a means of prototyping potential operational products. This project has demonstrated that approximately 1100 ocean products can be generated and available daily.

Coastal managers recognize the availability of this new capability but require a coordinated guidance from NOAA as a provider of coastal training and user support and commitment to a long-term continuous data stream.

This demonstration provides guidance for future operational monitoring of the coastal environment. The integration of advanced research products and their real-time availability as specialized data products is a reality. The report benchmarks examples of how NOAA distributes the monitoring and forecast capability and how customers such as the Mississippi Department of Marine Resources use these products.

This demonstration of “Ocean Weather” of the Gulf of Mexico represents the best scenario of ocean conditions from satellites and models readily available. The uncertainties and realignment of these products will identify the problems and lessons learned in product development. Recognize that the present capability is not the end system or defining set of products. The present real-time products provide a testing and evaluation of circulation models and uncertainty of satellite algorithms, and improved accuracy and products will evolve with customer requirements. .

This demonstration identified new capabilities for identifying and forecasting Harmful Algal Booms through research and operations. These capabilities build upon present NOAA capability and identify new methods based on experimental bio-optical satellite algorithms coupled with numerical models to improve HAB forecasts. This demonstration project benchmarks new methods and products for recognizing hypoxic conditions in coastal waters and for supporting shellfish management. Presently, ship measurement programs used by Gulf states use satellite data and models that rely on real-time conditions for determining optimal sampling locations. These measurements coupled with new satellite products such as salinity, PAR and turbidity fronts enhance the methods bywhich coastal managers determine the health of shellfish beds.

Future capability for forecasting and tracking ocean water masses is the next step for monitoring and protecting the ocean environment. The infrastructure of data flow for real-time assemblage of coastal conditions provides the framework to extend new products such as the 3-d bio-optical properties of the dynamic coast in additional to estimating the 24- and 48-hr forecast of conditions. This demonstration effort poses a challenge to coastal managers and NOAA operational centers in using the present capability and defining a roadmap for new products of the future.

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